MASS CUSTOMIZATION ASSESSMENT AND MEASUREMENT FRAMEWORK FOR INDUSTRIAL APPLICATIONS

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AALBORG UNIVERSITY
DENMARK

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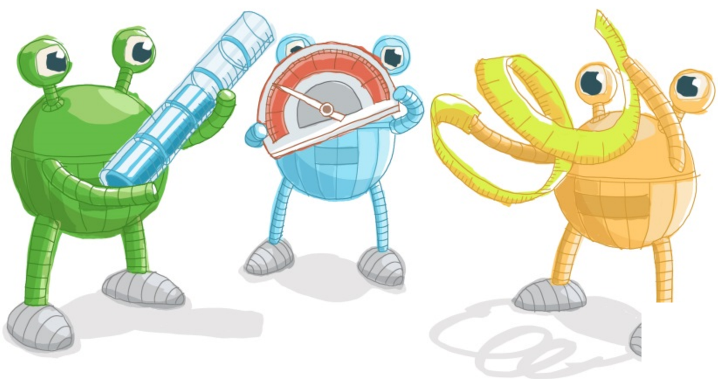

"NOBODY CAN GO BACK AND START A NEW BEGINNING, BUT ANYONE CAN START TODAY AND MAKE A NEW ENDING."

Maria Robinson, 7th President of Ireland

KJELD NIELSEN

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Aalborg University, Denmark
Department of Mechanical and Manufacturing Engineering
Doctoral School of Engineering and Science
The Faculty of Engineering and Science
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AALBORG UNIVERSITY
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Preface

In 2009 after some years as external examiner, external lecturer, supervising students, I was offered the opportunity to become a full time academic at the Department of Mechanical and Manufacturing Engineering. This was an opportunity to kick-start a third career and an offer my family and I found generous and also a very good timing seen in a lifetime perspective. I was expected to lecture and supervise half of my time and research the other half. It was destined that I had to present my research results in a PhD thesis. The department and Aalborg University offered me five years to fulfill my obligations, five years of half time lectures and supervising and half time research and documenting the research.

With LASAT Communication as an entrepreneur from the mid-80s to the end of the 90s, I was a practitioner with the responsibility of development and manufacturing of electronic consumer equipment. The products were at that moment state-of-the-art data communication boxes, modems (modulation-demodulation) which is analog electronic data equipment using the fix telephone lines as communication media (see figure I). The modems were developed in Denmark, manufactured in Far East, and sold in Europe and USA. As a result of extreme demands of data communications in the early 90' created on rising numbers of personal computers and the spread of inter-

Fig. I. Example of a product based on platform and modules.

net for commercial and consumer use, the need for speed and cheap products was inevitable. Speed of data on analog modems rose from 300 bit/sec to 56.6kbs in less than a decade and, in the same time frame, there was an exponential growth in market volume, as well as the sales price per unit was falling from 1000$ to 50$.

In general, every manufacturer of consumer electronics would face challenges as before mentioned. Developers and manufacturers of consumer electronic equipment's had to introduce new and innovative cost reduction methods, and on top of that several were forced to search for methods to overcome demands for country specific products, by implementing new technology in a speed almost faster than development engineering departments could adopt it. At the same time concurrent requirements for increasing manufacturing volumes, and request of reducing cost per units was demanded too (see figure II). The most important answer to these demands was substantial use of platform design and use of modules – terms well known to practitioners, engineers, designers and business managers today in concepts of fulfilling unique needs from costumers around the world, but those days in the early 90ties, we didn't know. The platform design and the use of modules was used both as tools for sales and production planning as well as design rules implementing new technology. We implemented platform designs and postponed assembly of specific products as close as possible to sale as an answer to the request for high degree of flexibility but without any skills and were successfully doing so just by coincidence and luck, and a lot of hard work. Today I know this is called mass customization. The practical and first hand experiences working with platforms and modules were the driver for initiating this PhD project.

A project spanning almost five years, with a theoretical outset and with practically no limitation to the research questions has been one of my life's biggest challenges to control. Goals and new goals have been set many times during this period. The project has from time to time been left alone due to other interests (responsibilities) at the

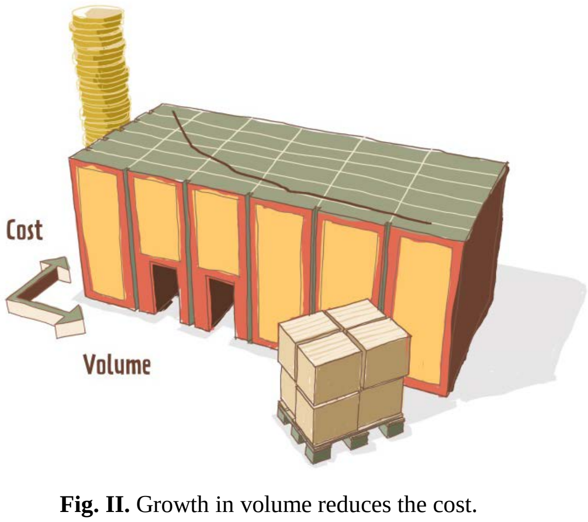

Fig. II. Growth in volume reduces the cost.

university. Coming back from other responsibilities re-starting the work with the project has been given advantages as well as disadvantages to the project. Often, new knowledge has been gained in the project between, moving objectives and resulting in new and other task than previously scheduled.

Regardless of these challenges, I succeeded in getting the project's scope shifted from a general view and broad perspective into a researcher's microscope and made a focus in an area of interest not only for myself but seems to contribute in a general exploitation of mass customization. During this process, I have to admit, probably as many other novel researchers before me that the road to the relative simple results and solutions seems to be endlessly complicated.

Initially, I did some research to identify state-of-the-art of enablers and drivers for mass customization especially the modularization of products as an enabler for mass customization - got my attention. Modules can be specific parts as we recognized them from the car-industry, engines, wheels etc. On the other hand modules in a mechatronic product can be represented as functions either as physical components like the wheels or engines in a car or as software modules just as we recognized them in our smartphone apps or in the laptop as programs. Doing my industrial career the success of our modem products could be nailed to the intense use of software. From the very early product types to the final used product platforms, we removed almost all mechanical parts and exchanged the mechanical functions with functions in software. Every small step moving from mechanical functions to software functions often replaced expensive mechanical parts with in-expensive software sub-routines One example would be a mechanical potentiometer regulating the loudspeaker volume, exchanged with a small software sub-routine would reduce not only the cost of the potentiometer but also require less space on the print circuit board and less space in the exterior of the product. Fewer components involved in the product would make the bill of materials shorter and cheaper, fewer components to mount making the manufacturing easier and the cost lower and on top of these advantages giving a potential to change the representation of function in with new software versions.

Five years, is a long time if one have to focus on one issue only – early in the period I recognized that it would be very difficult, if not impossible, if I had to keep close to the initial idea of the PhD project, and, luckily, in the same period the other half of my duties was practically much more than half. So relatively late in the five year period, the research has ended with the major contributions presented in this thesis, was defined as the research objectives. Previous research and results has not been useless; hence other colleagues with interest in these matters have gotten some ideas to work with it.

Even though it has been a long stretch and some early work has been discarded at least for the thesis and time being, the major task in this period have always been to become researcher – going back, to read, reflect, and conclude. Being taught to becoming an academic through a PhD program involves a lot of effort, both from the PhD student and the university. Presenting a PhD-thesis is not the end objective for a PhD student, but finding the path to be able to defend a PhD-thesis and hopefully some kind of scientific contribution, are now-a-day what the government, university, and Doctoral schools in Denmark aiming for. Getting new researchers prepared for

future tasks and with highest possible standard. Those who make rules and regulations for PhD students are constantly on quality guard to ensure a PhD student is given the absolute best foundation becoming our future researchers. Formal requirements like participation in high level PhD courses, education in reading and writing academic papers, presentation techniques, months stays at foreign university working with other research groups, and participation in the daily scientific work in a research group forms Danish enrolled PhD students to become a world class researchers.

My sincere thanks go to Aalborg University, The Faculty of Engineering and Science, Doctoral School of Engineering and Science, and Department of Mechanical and Manufacturing Engineering for have confidence in me and educating me to becoming an academic. Although the government and university has the system for PhD education in place, I have never been a PhD student or even got close to deliver the thesis you have in hand, without the support from a lot people. I would like to thank a lot of people, who one way or another have been involved in this thesis.

First of all, I would like to thank my supervisor Kaj A. Jørgensen. First, being my supervisor back in 1986 and after 23 years he still believed in me and made it all possible. Kaj has of all being a supervisor ensuring the academic challenges was alive and kept pushing high quality standards into the scientific work, Kaj will always be the research standard I will strive for in the future.

Secondly, I would like to thank my colleague Thomas Ditlev Brunø. Thomas and I work like buddies even though we have a span of age, where Thomas could be my son. Our mutual passion for aviation has cracked many issues arising when working closely and daily together. Thomas has been my source of inspiration when it comes to scientific communication and Thomas has been there in endless discussions when it comes to the scientific work and to the contributions in this thesis.

Thanks go also to Stig B. Taps, another close and good colleague of mine. Stig has, like me, late in his career decided to become an academia and in the early 00s he got his PhD. So Stig has been a great source of inspiration, when it comes to the challenges being a “grown up” in a world with young folks as PhD student colleagues.

Just as important, I would like to thank my family; first, for the tolerant and patient attitude when I stress, secondly for support to the project of becoming an academic, and great thanks especially to my lovely wife Marianne for always being there. Thanks to my son Lasse and daughter Line for their interest in the project. Thanks to Carlo, my dog for the daily support.

Finally to all my colleagues at the department and all my friends showing interest in the project, thank you for your great support.

Aalborg, October 2013

Kjeld Nielsen

Dansk sammendrag (Danish Summary)

Denne afhandling omhandler de udfordringer der kan opstå ved indførelse og drift af mass customization virksomhedsstrategi (kundetilpassede produkter). Dels i hvilken grad det er muligt at måle fremdriften i indførelsen af mass customization, og dels i hvilken grad kundetilpassede produkter kan tilpasses en grøn og miljøvenlig tilgang.

En undersøgelse fra 2012 viser at 17 % af de virksomheder der forsøger sig med at indføre mass customization strategien, inden for det første år indstiller mass customization aktiviteterne. Listen af virksomheder der forgæves har forsøgt sig, indeholder blandt andre den kendte jeans virksomhed Levi Strauss Company. Undersøgelsen gav ingen indikation hvorfor 17 % af de virksomheder der iværksatte en mass customization strategi, ikke fik succes eller i hvilken grad de øvrige havde succes. Dette faktum at der ikke findes et grundlag for at måle mass customization er det ene udgangspunkt for denne forskning. For 2 årtier siden blev mass customization introduceret, men først i 2009 blev det påvist af tyske forskere at det at kunne håndtere mass customization stategi kræver kapabilitet i 3 fundamentale områder. 1) styring af produktudvikling, 2) robuste produktion processer, og 3) styring af produktdata, netop denne viden er grundlaget for det andet udgangspunkt. Afhandlingen påviser at det er muligt dels at opbygge en rammestruktur for målinger med udgangspunkt i de 3 fundamentale kapabiliteter og dels at det er muligt påvise en række metrikker der kan måle mass customization processen indenfor disse 3 fundamentale kapabiliteter. Metrikkerne giver mulighed for målingerne der baseret på kendte og tilgængelige data der forefindes i stort set alle virksomheder – hvilket gør det relativt let at tilpasse eksisterende driftssoftware, således at afhandlingens resultater kan anvendes i industrien.

Udover de nævnte metrikker har forskningen der ligger til grund for afhandlingen ført til ny viden om sammenhængen mellem mass customization og miljørigtig tilgang. For effektivt at kunne levere kundetilpassede produkter kræves det at produkterne er bygget på moduler, som med LEGO klodser at kunne bygge produktet ud fra kendte moduler. At forberede produkterne til modulopbygning kræver at der anvendes forskellige værktøjer og metoder som er ganske velkendte i f.eks. bilindustrien. På lignende vis er der over de seneste årtier opbygget metoder og værktøjer der støtte virksomheder i at udvikle og designe miljø rigtige og grønne produkter. Denne afhandling påviser at de anvendte metoder og værktøjer for henholdsvis at kunne forfølge en mass customization strategi og have en miljørigtig tilgang med virksomhedens produkter, ikke forhindres og i flere forhold understøtter de forskellige mål der måtte være.

English Summary

This thesis addresses issues in management of mass customization: 1) the ability to assess and measure mass customization progress, 2) in what degree supplement mass customization sustainable product design.

Mass customization is a business strategy to approach customers with one of kind products. Following this strategy, business managers has several pit falls and barriers to become and maintain being a mass customizer. A recent survey has exposed these barriers being a mass customizer culminates with massive 17 % unsuccessful companies failing the mass customization business strategy within the first year. In the list of unrewarding mass customizers is well known jeans company Levis.

Mass customization has been around for the last two decades but first recently a structural approach to mass customization was acknowledge addressing mass customization with three fundamental capabilities. This novel research has opened for research in the direction of supporting industrial applications of mass customization. The three fundamental capabilities covers 1) development of products – solution space development, agile and flexible manufacturing, 2) robust process design, and 3) product configuration and product specifications – choice navigation. Altogether, three capabilities embracing the mass customization processes.

The previously mentioned survey has no indication of what makes mass customizers successful or not. Hence, this observation has been the foundation for this thesis, i.e. to establish a framework and identify key performance indicators, which will assist practitioners in how to become a mass customizer and how to maintain such a development. This thesis presents metrics achieving assessment and measuring within the three fundamental capabilities in given areas of the mass customization progress. The data for these metrics are based on availability in currently used IT systems, which make it possible to develop industrial applications.

Besides the metrics for mass customization, this work presents findings in sustainable mass customization. One enabler for mass customization is modularity, and several methods and tools for modularity has been presented and implemented during the last two decades in companies around the world. Some are for preparation to become a mass customizer and others can support the fact that modular products offer several benefits in manufacturing. The automotive industry, for example, has adopted modularity long time ago, seen as the ultimate exploiting in VWs setup in cross brand modules. This research contributes with new knowledge about becoming a mass customizer using the procedures, methods and tools for modularity and at the same time supplement a sustainable approach using ECO-design procedures, methods and tools.

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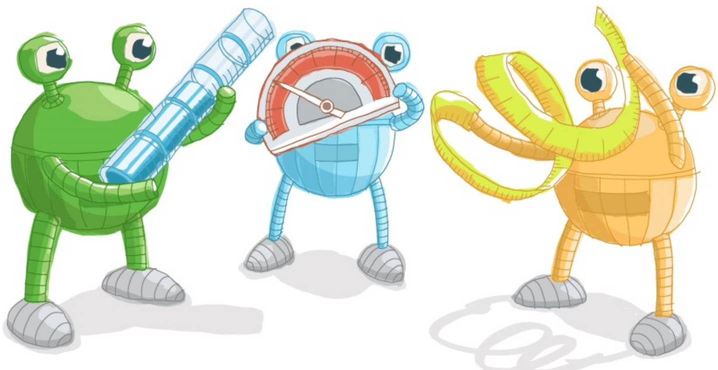
PART I

EXTENDED SUMMARY



1

Introduction

This chapter presents the foundation for the scientific work as well as some considerations or initial problem analyses made prior to final decision about research paradigm, methods, problems and specific research questions. Relations between the academic work presented in this thesis and consideration in direction of industrial applications is a part of this introduction as well. The chapter has been organized in two sections with modules and sustainability as the first section, and mass customization as the other. The correlation between the considerations, the research and results in papers included in this thesis are part of the presentation in these sections.

1.1 Modules and Sustainability

Modules and platform designs have been around for decades, our Swedish colleagues Ericsson and Erixson [1999] presented in the 90s tools to recognize the best candidates of modules in a product, successfully used by Scania and other successful major companies in Sweden. Methods and tools focusing on mechanical parts and with drivers giving the company advantage in business competition and improving the company's profit; others like Ulrich and Eppinger [1991] have presented similar tools with different drivers for platforms and modules. Since the early days of mass customization, Pine [1993] and other researchers [Davis, 1989; Gilmore & Pine II, 1997; Tseng & Jiao, 1996] have pin pointed modules as the major enabler for mass customization, but lack of knowledge about the drivers for modules in relation to mass customization pointed to research on the relationship for enablers and drivers in relation to mass customization. When doing this part of the project and doing work with sustainability, it was recognized that tools and methods used to develop sustainable products are similar to those used for modularity – different enablers and various drivers aiming at different kind of sustainable objectives and design rules. Because of the research and analysis of the drivers for modularity, the inspiration to such analysis as well for sustainability was implemented in the project. Would it be possible to design products aiming for maximum flexibility, with modules and platforms in a mass customization environment and at the same time are able to follow drivers and rules in sustainable designs? Or with another viewpoint, would sustainable design rules or drivers be interfering with drivers for modularity? Drivers for modularization and rules for sustainability have been compared to address any fit or mismatch between these design roads. Paper 1 included in the thesis is a documentation of this research carried out as a comparison of selected methods for modularity and selected rules for sustainable design and paper 3 presents the result of an explorative analysis of the hierarchy of ECO design and mass customization. Furthermore this research has been extended to analyses of sustainable handling of products in the phase of end-of-life, because of the nature of mass customized products, the uniqueness products, disassembly and other typically used standardized methods in end-of-life can be expected to cause problems for mass customized products. Paper 2 included in this thesis is a documentation of this work.

1.2 Mass Customization

Mass customization is one strategy to follow if Danish industry is to keep up with the (growing) competition from other nations. Since the economic crisis (started in 2008), the world been set on hold, political winds seem to ease the load of Danish industry

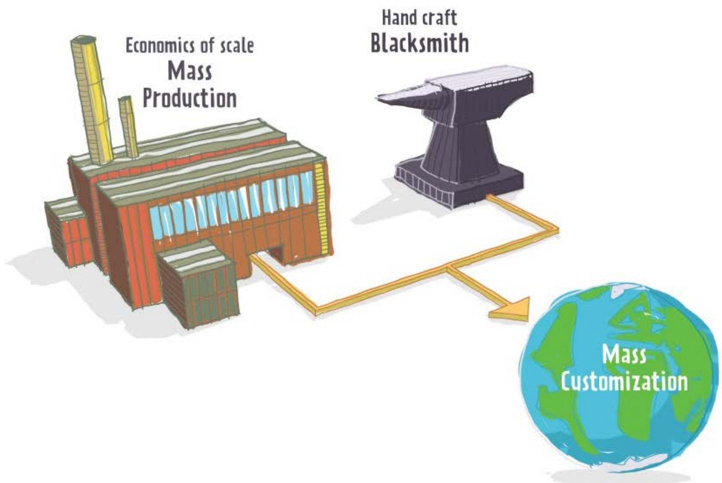


Fig. 1. *Mass production and craft production are coined, to mass customization by Davis [1987] – in the early days an oxymoron; today well known business strategy.*

with lower taxes and other political tools to make the industry including the workforce global competitive. Unfortunately, recent research has indicated that becoming a mass customizer has its challenges – a survey reveals that up to 17% of companies started to become mass customizers fall out of the mass customization strategy within the first year [Walcher & Piller, 2012]. A lot of start-ups and new businesses are among the 17% but industry leading companies like Levi Strauss Company have left the mass customization strategy as well. A scientific investigation of root-cause for the 17% has not been part of the survey so any assumption of root-cause is as good as others when accounting for the results. It is questionable to which degree mass customizers have evidence about their mass customization status or progress because no such holistic knowledge of methods or tools to analyze mass customization progress was present before when this project was initiated. The missing information about mass customization progress or industrial application assisting managers at any level in decision the making progress implementing and managing mass customization have been the outset for the rest of thesis. This part of the thesis is the principal part with both research results ready to use, but also a potential opening for several new scientific hypothesis and research project.

Measurement of a progress has never been a trivial task even though it seems obvious that implementing a measurement tool could straightforward. Since the early days of mass customization, drivers, enablers, methods, and tools have been presented as the unquestionable road in quest of assisting the industry becoming a mass customizer, which the state-of-the-art sections indicate strongly. It seems that most researchers needed a light house to take the big step in mass customization, a light house like the book "mass customization – the new frontier in business" [Pine, 1993] – which was the first business approach to mass customization strategy. Followed by the next big light house – and a lot of smaller light houses in between – but a really big light house

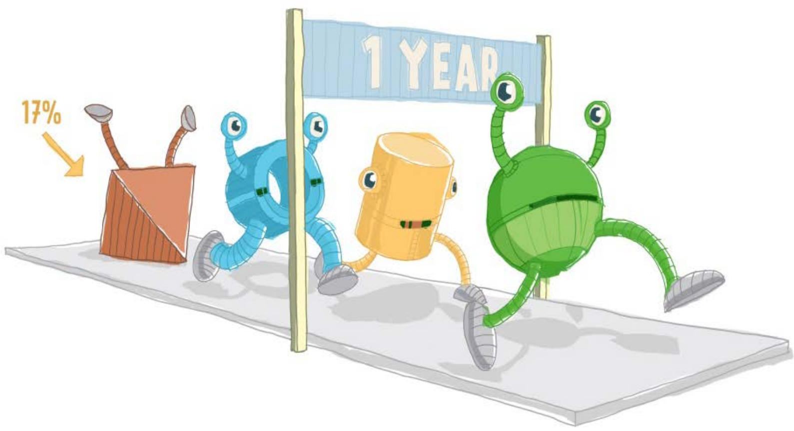


Fig. 2. *17 % of companies have failed challenging mass customization within the first year [Walcher & Piller, 2012]*

came in 2009 from Salvador, de Holan and Piller with “Cracking the Code of Mass Customization” [2009]. They introduced the three fundamental capabilities in mass customization, i.e. the definition of three fundamental capabilities. Hence, a feasible foundation for work like the research in this thesis was introduced. It gave an opportunity to share the work with equal minded peers as well as non-academia. Pine [1993] pinpointed that companies going to follow mass customization strategies should consider if they had the drivers enablers for mass customization, i.e. need for unique products or product variety and would they be able to follow some of the elementary enablers such as using modules, and postponement in manufacturing. The latter authors have on the other hand pinpointed the need for solution Space Development (product development, skills), Robust Process Design (manufacturing and process skill), and Choice Navigation (configuration skills).

Solution space development as defined by Salvador et al. [2009] is a matter of identifying your customers need before they know the needs and accordingly decide which products or variety you will offer your customers. One example of following this approach is the way Fiat managers chose the design and developed offered variety for the new Fiat 500, using tools offering potential customers before the Fiat 500 was finally designed asking these potential customers what kind of expectations and variety would they prefer in the new Fiat 500 – with more than 100.000 replies, Fiat was overwhelmed with design ideas and suggestions of varieties, enough to choose from and one of the sources for the variety offered, when the Fiat 500 finally was launched [Salvador et al., 2009]. This is a program, which still exists – open for all interested – and with rewards for the month’s best idea. Fiat will for next many years have a source for solution space development of Fiat 500.

Robust Process Design is defined as the capability of re-using and re-combining organizational and value chain resources to fulfill differentiated customers’ needs;

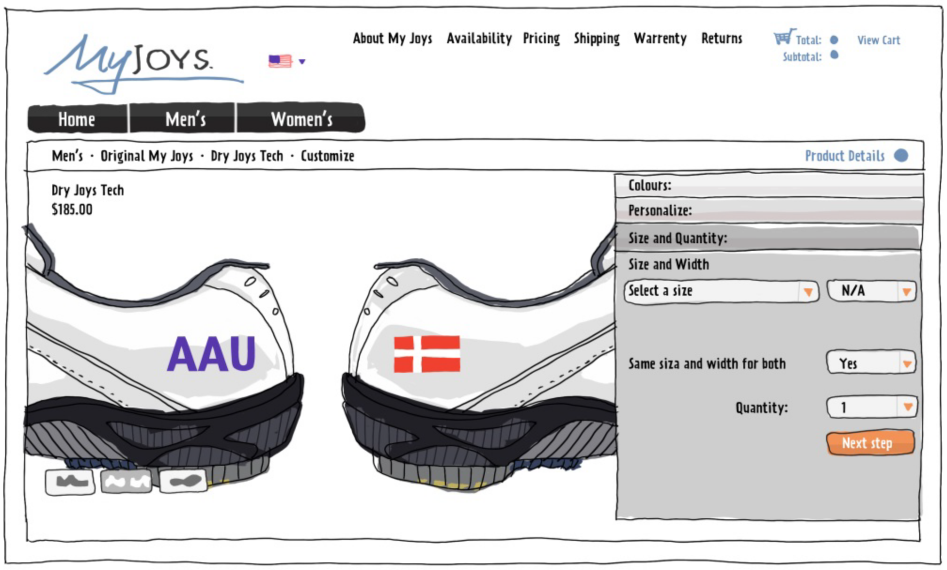


Fig. 3. *Example of Choice Navigation/ product configuration – FootJoys (source: www.myjoys.com)*

both in manufacturing systems as well as human resources. Just a decade ago, the term flexible automation would have been a contradiction. The German automotive industries have proofed otherwise and in Denmark, major manufactures as Grundfos have invested in research supporting flexible automation. Heavy research assisting the industry in flexible automation is evident and an early indication of European Union's next research platform Horizon 2020 has this research as a major focus area. Examples from BMWs Mini production clarify that Mini manufacturing can be changed with small manufacturing cell called MobiCells [Wiendahl et al., 2007], the time from defined task until operation can be as low as few days [Mortimer, 2007; Piller et al., 2012b].

The last of three capabilities, Choice Navigation, expresses that a company's ability to support customers in identifying their own problems and solutions, while minimizing complexity and burden of choice. As the Footjoy golf shoes product configurator or the example with M&M (see figure 3 and figure 4), the customer is taught to configure and on the other hand the configurator collects data about preferred choice and selection, which can assist the system in addressing styles and variants fulfilling the customers' needs. Regardless whether the customer purchases the product, valuable information has been collected about customer needs and the individual customers' preferences.

In this research, it was recognized that few contributions of "how to assess and measure" the above mentioned three fundamental capabilities have been made. On the other hand reviews also indicate that the years before the three fundamental capabilities were published, only few have worked on tools and methods assisting mass customization strategy and industrial applications. Some work was done in the early 00's, but they seem to have foundered for unknown reasons, possibly because no such foundation as the three fundamental capabilities existed.

The work with the above presented three fundamental capabilities have been used as the foundation for the research to present methods and tools to assess and measure a given mass customizer's mass customization management, with the objective of assisting him in 1) becoming a better mass customizer and 2) be able to benchmark against other mass customizer, 3) benchmark against mass customizer companies best in class.

This thesis will contribute with 1) new knowledge in the field of mass customization 2) new knowledge of metrics and key performance indicators for mass customization, 3) and finally new knowledge about the relationships between drivers for sustainable product design view and drivers for mass customization.

The thesis has been organized in two parts; the first part is the main thesis, which beside this Introduction has a State-of-the-art chapter, a chapter with scientific approach and methods, a chapter with objectives, hypotheses and research questions, two chapters with results, and finally conclusions with perspectives and further research. The second part includes the nine main scientific papers, which have been collected for the thesis.

2

State-of-the-art

This chapter presents state-of-the-art in mass customization. The state-of-the-art has been divided into three sections addressing the different domains involved in the research covered by this thesis.

2.1 Mass Customization and Capabilities

Mass Customization is long known as a competitive strategy for delivering individually customized products at costs near mass production, bringing inexpensive tailored products to the end customer. Applying mass customization implies a number of benefits to companies: The ability to charge a price premium [Gilmore & Pine, 2000; Piller, 2004; Pine et al., 1993] and economies of integration giving access to market information and customer loyalty [Piller et al., 2012b; Salvador et al., 2009; Walcher & Piller, 2012]. Prominent examples of mass customization includes customized computers from Dell, which are all configured to individual customers' requirements, Custom shoes from Adidas or Nike as well as the car industry where mass customization is widely adopted allowing customers to configure hundreds of different options within a specific car model or as M&M offer chocolate (see figure 4).

Stan Davis was the first to coin the term "Mass Customization" in his bestseller *Future Perfect* in 1987 [Davis, 1987; Davis, 1989]. Following this, companies around the world have recognized mass customization in an attempt to avoid consequences of trying to meet every customer's need [Gilmore & Pine II, 1997; Gilmore & Pine, 2000; Gilmore & Pine, 2007].

In the shift of paradigm from mass production to mass customization, manufacturers have increased significantly the number of product varieties offered to consumers over the past several decades. An example, the number of distinct vehicle models in the U.S. increased from 44 in 1969 to 165 in 2006 [Hu, 2013]. Within each model, there can be many choices on the powertrain and interior combinations. Another example is the styles of running shoes offered by Nike or Adidas or golf shoes offered by FootJoy (see figure 3). All three companies have adopted the mass customization strategy and have increased from few models to many models with almost infinitive variety. New research has intensified in building user needs, using 3D scanners and 3D models [Fogliatto et al., 2012; Piller et al., 2012a], which could bring manufacturing process to the ultimate 3D printing process [Klein et al., 2013]. The increase has been driven by the need to provide high variety and highly customized products in response to the idiosyncratic customer needs and customer preferences [Salvador et al., 2009].

It has long been known that shifting to a mass customization focus has proven difficult in practice, and many companies have made an attempt, but failed and returned to a traditional mass production strategy with economic loss [Pollard et al., 2011; Zipkin, 2001]. For this reason, much research has focused on identifying the different enablers for achieving mass customization. Silveira et al. and Fogliatto [2001; 2012] present an overview of the research into mass customization enablers, which by Fogliatto et al. [2012] is divided into the categories: 1) Methodologies, 2) design processes, 3) manufacturing processes, 4) supply chain coordination, 5) manufacturing technologies and 6) information technologies.

The reason why shifting to mass customization is so difficult is that it is fundamentally different than mass production. In product development, families of products must be developed instead of individual products. In the sales process, vast amounts of information must be exchanged between customer and company to configure the

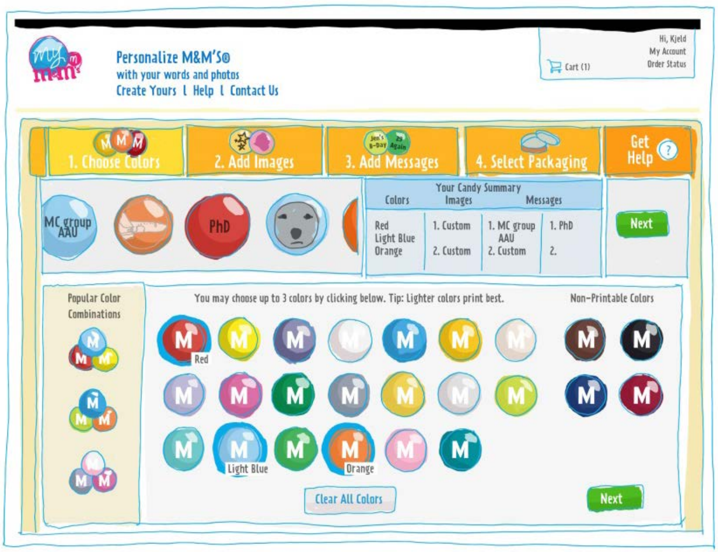


Fig. 4. *Example of product configuration – M&Ms (source: www.mymms.com)*

right product and allowing the company to manufacture it. In manufacturing, products are manufactured in batches of one as opposed to mass production where batches are hundreds or thousands of identical products. This basically renders a mass production system useless in relation to mass customization manufacturing.

In relation to logistics, a specific product must be moved from the manufacturing facility to the end customer, whereas in mass production a number of products are shipped from the manufacturer to a warehouse to a retailer where it is sold to the end customer. This further introduces a challenge since mass customization products cannot be stocked and can only be produced once a customer order is given. All the challenges described above need to be addressed if a company wishes to pursue an mass customization strategy, which in many cases has proven more difficult than anticipated.

Recent research has shown that the ability to transform a business into a successful mass customization business depends largely on three fundamental capabilities (see figure 5) [Salvador et al., 2009]: 1) Robust Process Design – Reusing or recombining existing organizational and value chain resources to fulfill a stream of differentiated customer needs, 2) Solution Space Development – Identifying the attributes along which customer needs diverge and 3) Choice Navigation – Supporting customers in identifying their own solutions while minimizing complexity and the burden of choice. Hence a company mastering each of these three fundamental capabilities has increased chances of succeeding as a mass customizer. Although these three capabilities are identified and described, mass customization companies are still faced with a challenge when evaluating their capabilities to identify where performance lacks since no integrated method is available serving this purpose. A number of isolated perfor-

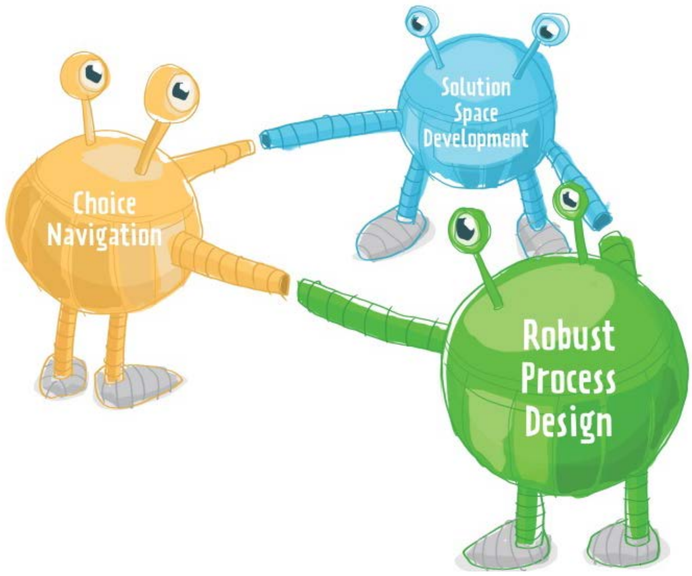


Fig. 5. *Three fundamental capabilities Solutions Space Development, Robust Process Design and Choice Navigation, according to Salvador et al. [2009]*

mance measures for mass customization has been presented in literature, which will be presented in the following related to each of the three mass customization capabilities.

Robust Process Design

Related to robust process design, some research has also focused on evaluation and benchmarking. Yang & Li adapted a method for evaluating a firms manufacturing agility to assess their mass customization manufacturing capabilities [Yang & Li, 2002]. Blecker et al. [2003a; 2003b] introduced a number of performance indicators in relation to mass customization manufacturing; however these were intended to support decisions regarding product variety rather than assessing manufacturing capabilities. Zhang et al. [2011] analyzed the relationship in mass customization manufacturing firms between the independent variables: product elicitation process, flexibility in design, usage of advanced manufacturing technologies, just in time supply chains, and integrated logistics information system and the dependent variables: Cost, Product/service quality and financial performance. Using a large sample of mass customization firms, this research is useful for identifying factors influencing robust process design; however it is less useful for assessing individual firms' performance since it is based on qualitative assessments by managers. Daaboul et al. [2011] introduced a number of metrics related to the robustness of processes, however in the context of balancing the customer value of product variety with the cost of increasing process variety needed for customizing products.

A gap analysis of the state-of-the-art in Robust Process Design indicates that present contributions identify agility, variety and other factors related to flexible manufacturing decisions rather than assessing and measuring the robust process design progress.

Solution Space Development

Kumar [2004] formulated a number of metrics for customization, mass production and modularity, thereby measuring the number of modules, combinations and theoretical production volume per module. These metrics are useful in relation to describing the variety of a product family; however less useful in relation to assessing whether some options are configured less frequently than others potentially rendering them less profitable. Furthermore, these methods do not enable assessment of whether the variety offered is actually the variety demanded by customers. Several authors approach the design problem in developing mass customization products effectively by quantifying customer value and estimating product cost [Gonzalez-Zugasti et al., 2001; Jiao & Tseng, 2004; Martin & Ishii, 2002]. However, none of these are found to provide metrics which are useful for assessing an existing solution space. Blecker et al. [2003a] presented an extensive system of metrics for variety steering very relevant for assessing solution space development.

Based on a sub-process model representing the essential sub-processes of mass customization a number of metrics are identified to form a system able to assist in making decisions regarding variety. Hence the work aims at providing a tool for solution space decisions rather than providing an assessment. Schuh et al. [2011] developed an integrative assessment tool for assessing metrics such as “fit of variety”, “product architecture flexibility” and “explainability at point of sale” along with manufacturing metrics to address the dilemma between economies of scale and economies of scope. As found in the-state-of-the-art intensive research approaching solution space has been done, this also indicates that none of this work have been directed against assessing and measuring status of solution space development.

Choice Navigation

One of the most extensive studies on choice navigation is the survey “Customization 500” by Walcher and Piller [2012]. This study analyzed 500 different mass customization firms and their product configurators and thereby their ability to perform choice navigation. Even though a very extensive survey the results in the survey are very difficult for the individual companies to translate into activities necessary becoming a better mass customizer. Blecker et al. [2003a] described a number of metrics that could be used for assessing the capability for choice navigation, including Average configuration length of time, configuration abortion rate, as well as rates of which mass customization companies introduce and eliminate product options. Most of those metrics are useful; however how they are linked to overall mass customization performance is not addressed in that research. Trentin et al. [2011] analyzed the relationship between configurator usage (i.e. how choice navigation is performed) and time performance, e.g. on time delivery performance, cycle time, speed of new product introduction. This research was significant in validating that choice navigation is

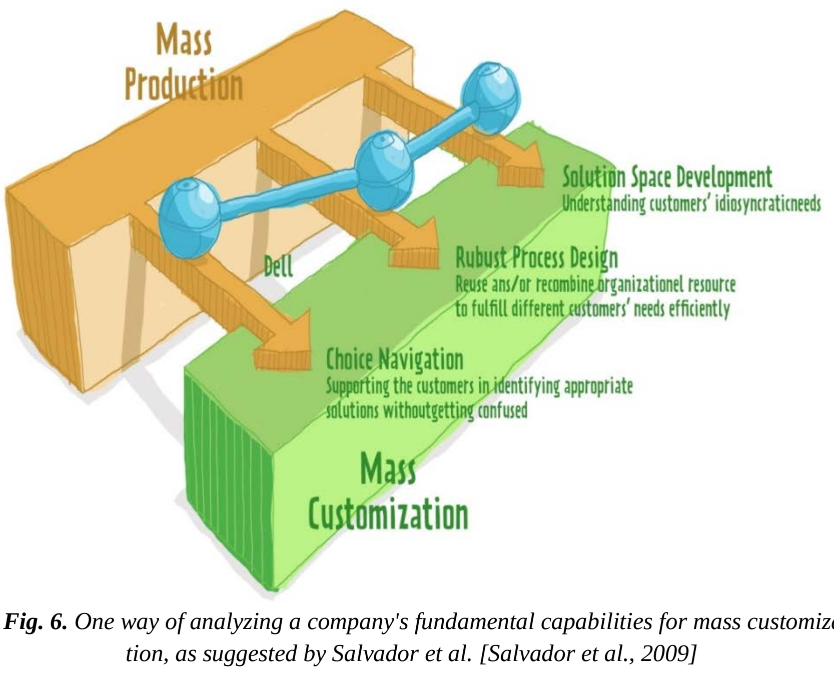


Fig. 6. *One way of analyzing a company's fundamental capabilities for mass customization, as suggested by Salvador et al. [Salvador et al., 2009]*

critical to overall performance and also indicates a number of possible metrics. However since the research relies on managers' qualitative assessments, it is less useful for making capability assessments of individual firms. Other research indicates the benefits companies can apply from product configuration in the specification process [Hvam et al., 2010]. Engineer to order industries has often well specified product families but the unique products fitting individual customers often has to be specified on individual basis, nevertheless research in this do not apply any assessment or measurement in general about Choice Navigation. The state-of-the-art indicates that some metrics have proven useful to assess Choice Navigation and on the other hand indicates gaps to be filled.

2.2 Mass Customization and Assessment

In the article "Cracking the Code of Mass Customization" Salvador et al. [2009] argue against the common executive perception of MCPC as a "fascinating but impractical idea", by introducing the concept of 3 fundamental capabilities as success factors, based on the results from substantial research of 238 companies in eight countries. The three capabilities are each supported by three approaches to achieve that specific capability. Each capability is described as a continuum i.e. a company can be extremely capable, not capable at all or anything in between in relation to each capability. A company being highly capable within each of the three capabilities could thus be considered the ideal mass customizer, whereas a company being less capable would indicate a mass production company not very capable of mass customizing. An example of mapping the three capabilities is shown in figure 6. Identifying for which capability a company has the lowest performance (being least capable), would thus help the company identify where to focus its effort to boost its chances of success in a mass customization market.

2.3 Mass Customization and Sustainability

Organizations in general, NGO's, private and business movements, costumers' organization, are all stakeholders, who have addressed the sustainability domain. Much of this work has been used as an off-set for sustainability in general, as seen in the Bruntland report [Brundtland, 1987; Hueting, 1990] and the Hannover principles [McDonough & Braungart, 1992] used as foundation for the Cradle-to-Cradle. Governments have set sustainability on top of the list, as information about environmental issues, behavioral education and with legislation, which requires manufacturers to address the issues of sustainability [Hall & Vredenburg, 2003; Karlsson & Luttropp, 2006; Lindhqvist et al., 2011; Maxwell & Van der Vorst, 2003; SDC-UK, 2011]. On the other hand a request for sustainability is driven by costumers, which also leaves the manufactures with a need for fulfilling these requirements [Klöpffer, 2003; Linton, 2005; Manzini & Vezzoli, 2003; Seuring & Muller, 2008].

Mass customization has by some been regarded as a concept which increases the demand for quick replacement of consumer products and is thus potentially unsustainable [Czarnecki et al., 2005], since shorter life cycles will usually imply greater material and energy consumption. However, it has not been possible to identify studies that thoroughly investigate the relationship between mass customization and sustainability.

Since sustainability is a concept that is gaining more and more attention, and companies are experiencing a greater demand for sustainable products as well as legislation requiring lower environmental impacts [DSI, 1996] sustainability must also be addressed in relation to mass customization. Several concepts are commonly applied to achieve greater sustainability in product design and manufacturing. Among these is ECO-design, which is a concept that attempts to integrate environmental aspects into the product development process thereby creating products with lower negative environmental impacts and thus more environmentally sustainable products [DSI, 1996]. Sakao & Fargnoli [2010] analyzed the relationship between ECO-design and mass customization and concluded that mass customization not only presents challenges but also a number of opportunities for designing more sustainable products. Romero et al. [2011] addressed this issue in more depth in relation to computer aided ECO-design, describing how computer aided tools can allow for easier life cycle assessment and thus more sustainable products. In relation to ECO-design and mass customization, Lei et al. [2007] addressed the need for a green product configurator, where an information model supporting assessment of sustainability along a configuration process was presented.

Boër et al. [2013] developed a sustainability assessment model taking into account not only the environmental dimension but also the economic and social dimensions of sustainability, specifically for mass customization products. Based on this model a number of products were analyzed and it was concluded that it cannot be concluded whether or not mass customization promotes sustainability.

3

Objectives and Hypotheses

This chapter is a collection of objectives and hypotheses made ready for the thesis. The objectives, hypotheses and research questions have been adjusted trimmed to address the research with highest standard and expectations. Each objective has been addressed and evaluated individually with the purpose of clarifying the necessity of its scientific importance and its expected contribution. The objectives have been transformed in to 3 hypotheses and each hypothesis has been supported by several research questions.

Though Mass Customization has been around for more than two decades, the knowledge about interaction between mass customization capabilities does not satisfy the need in industry nor academia. Research indicates that the fundamental capabilities, tools and methods suggested as a frame for implementing and exploiting mass customization, from time to time fail and in worst case scenarios result in abandoning the mass customization strategy. The hypotheses are formed on the assumption that it is possible to establish metrics based on well-known data in any given company, measuring the three fundamental capabilities. Initially the scientific objective for this research has been:

INITIAL SCIENTIFIC OBJECTIVE

- *Contribute to existing theory in the field of mass customization.*

The theoretical objective will contribute to knowledge, definitions and models and a better understanding of the relationship within mass customizations methods and tools and how these tools and methods can support the exploitation of mass customization.

3.1 Objectives

Practitioners should from the practical objectives of this research benefit from new models and methods, making the practitioners and business manager capable to monitor implementing mass customization, assessing and measuring the status of mass customization and be able to benchmark.

MAIN OBJECTIVES

- *Contribute with a framework for assessment and measurement of industrial application of mass customization.*
- *Contribute by identifying known metrics measuring mass customization.*
- *Contribute with development of new metrics for measuring mass customization.*
- *Contribute with knowledge about variables and parameters relationship for assessment and measurement of mass customization.*

ADDITIONAL OBJECTIVES

- *Contribute with knowledge about modularization enablers in different method approaches for personalization and their relationships to design for sustainable products*
- *Contribute with new knowledge about closed loop supply chains and sustainable mass customization.*

The objectives above have been extracted from the work with state-of-the-art in the area of mass customization, with the main objective of closing the gap between the science of mass customization and commercial use of mass customization. On the other hand any kind of commercial business does today involve sustainable thinking in parallel research to the research with measurement and assessment of mass customization, research involving sustainability and mass customization has been done.

3.2 Hypotheses

Hypothesis 1, addresses the overall and general approach to assessment and measurement framework, seeking for findings supporting that such framework can be established.

HYPOTHESIS 1

IT IS POSSIBLE TO ESTABLISH A FRAMEWORK FOR
ASSESSMENT AND MEASUREMENT OF PROGRESS OF MASS
CUSTOMIZATION

Hypothesis 1 is expected to be clarified with these research questions:

1. How can a generalized framework understanding the fundamentals in assessment and measurement of mass customization be established?
2. Can the approaches as described in the three fundamental capabilities by Salvador et al. [Salvador et al., 2009] be uses as the outset for identifying and development metrics assessing and/or measuring mass customization?

Hypothesis 2 addresses the specific tools to assess and measure mass customization:

HYPOTHESIS 2

IT IS POSSIBLE TO IDENTIFY OR DEVELOP METRICS FOR ASSESSMENT AND MEASUREMENT OF MASS CUSTOMIZATION PROGRESS

Hypothesis 2 is expected to be clarified with these research questions:

1. Can metrics be identified or developed indicating progress or status for product development in a mass customization framework?
2. Can metrics be identified or developed indicating progress or status for production process in a mass customization frame work?
3. Can metrics be identified or developed indicating progress or status for product configuration in a mass customization framework?

Hypothesis 3 addresses how well mass customization and sustainable designs correlate.

HYPOTHESIS 3

IT IS POSSIBLE TO BE A MASS CUSTOMIZER AND AT THE SAME TIME BE SUSTAINABLE

Hypothesis 3 is expected to be clarified with these research questions:

1. Can enablers in mass customization like modules work along with similar enablers in sustainable design?
2. Can products designed for mass customization – one-of-a-kind products – adapted in closed loop supply chains?
3. Can mass customization support ECO-design hierarchies?

4

Research Methods

In this chapter, the specific research approach is designed. Arbnor and Bjerke [2008] present a framework, which suggests that ultimate presumptions contained within a paradigm through theory of science is the basis for determining a methodological approach. The methodological approach is then the basis for the design of the research design, containing methods and procedures, which can be applied to a certain study area.

4.1 Scientific Paradigms

Researchers may have different presumptions about the world and this has influence on the way they address certain problems and usage of techniques. A commonly used term for a set of ultimate presumptions is a paradigm as introduced by Kuhn [1996].. A paradigm is a set of presumptions, values and ideals, typically within a certain scientific area.

Several authors have proposed different classifications of paradigms. Some authors promote only two views, i.e. a positivistic and hermeneutic [Coughlan & Coghlan, 2002; Gummesson, 2000] while others argue for three simultaneous paradigms [Arbnor & Bjerke, 2008]. Others even promote four classes: positivism, post positivism, critical theory and constructivism [Guba, 1990] or post positivism, constructivism, advocacy/participatory and pragmatism [Creswell et al., 2003]. The paradigm Critical Rationalism is considered fundamental for research work within this project. Critical rationalism introduced by Popper [1959] is the theory, of which one of the main elements is the theory of falsification first introduced by Popper [1935]. The principle of falsification is that a general acknowledged theory could be falsified by a single observation that proves the theory wrong; see e.g. the black swan example

[Schroeder-Heister, 2001]. Popper argued that besides focusing on proving theories, researchers should also focus on proving theories wrong, i.e. falsifying them, to prove their validity.

The concept of critical rationalism developed by Popper is in short that "Theoretical progress is made by successive critique and revision of existing theories, which is governed by the idea of objective truth" [Schroeder-Heister, 2001]. According to this statement, falsification may be used not only to reject scientific theories but rather in an approach to improve existing theories by falsifying them and revising the existing theories to encompass the observation, which had originally falsified it [Schroeder-Heister, 2001].

From this, it follows that a scientific theory can never be considered as final, since the theory may at some point be falsified on basis of new knowledge or observations and hence it is never certain that a theory describes the whole truth. However, when a theory is falsified and subsequently revised, the new theory will always be closer to truth than the falsified theory [Schroeder-Heister, 2001].

Much business research has focused on applying principles from one business area to other business areas which are different from the original one. This process can be perceived as a continuous expansion of business theories, where the application of a theory to a new area is potentially a falsification of the current theory. If the theory can be applied to the new business area, the theory is not falsified but the set of observations not falsifying the theory is expanded. In this case the theory will of course also be practically applicable to more cases and new business knowledge is created with a potential to create value in companies.

If the theory however is falsified, the theory can be revised, typically through a specialization of the existing theory or development of supplemental theories. In this case the body of theory also becomes more encompassing than previously and thus applicable in more practical cases in companies.

Finally, if the business theory is falsified and it cannot be revised in such a way it is applicable to the new area, the new more encompassing theory will simply state that the original theory has limitations regarding the new area, and thus new business knowledge is also created in this case.

Critical rationalism is thus highly relevant to this project since the approach described above has been applied to this project in order to identify theories and methods from mass customization, product configuration, etc. and determine whether they can be applied to the research area. In critical rationalism terms, this project attempts to revise and further develop the existing theory to increase the theoretic business knowledge.

4.2 Research Methodologies and Selected Approach

Arbnor and Bjerke [2008] argue that the set of ultimate presumptions and thereby the scientific paradigms is determinant for the methodological approach that should be applied in different research ventures. The three main methodological approaches as identified by Arbnor and Bjerke [2008] are:

- The Analytical approach
- The Systems approach
- The Actors approach

According to Arbnor and Bjerke [2008] one of the main characteristics of the analytical approach that distinguishes it from the systems approach is its summative character. This can be summarized in the statement “The whole is the sum of its parts” [Arbnor & Bjerke, 2008]. This implies that the analytical approach addresses research problems isolated, and seeks to develop a theory within a delimited area without emphasizing relations to other areas.

The systems approach can be summarized in the statement “The whole differs from the sum of its parts” [Arbnor & Bjerke, 2008]. This implies that contrary to the analytical approach, research problems are not addressed as isolated problems, but a research area is regarded as a number of problems which need to be addressed as a whole, and the relations between the problems and their implications are taken into account. Furthermore the systems approach assumes that knowledge about a certain issue is highly dependent on the system, which the issue is a part of.

In the context of this project, the analytical approach would imply seeking to develop solutions, which are independent of the system the solutions are being applied in. Contrary to this, in a systems approach, the solutions are developed under the assumption that there does not exist a single approach to mass customization that produces optimal results in all systems.

According to Arbnor and Bjerke [2008] the third approach, the actors approach is mainly relevant in relation to social research. Relating the actors approach to this project would imply analyzing the social structures related to the research area, and thereby organizational issues will be emphasized. According to Arbnor and Bjerke [2008] the systemic characteristics will both be relevant for the actors approach but mainly actors meanings, perceptions and relations between each other are the subject of interest.

4.3 Research Design

This project uses the systems approach according to the definition from Arbnor and Bjerke [2008]. In order to give based on basic principles of general systems theory, Joergensen [2000] describes a methodological procedure commonly used for conduction research and development projects. Hence a methodological procedure which is based on systems theory seems to be an appropriate approach. The methodological procedure is based on the two fundamental system concepts analysis and synthesis. Joergensen [2000] defines these two concepts the following way:

- Analysis (of an existing system) is 1) to investigate properties of the system and 2) to divide the system into system components and system structure.
- Synthesis (of a new system) is 1) to create the system by relating existing systems to each other by a structure and 2) to add properties to the system.

Joergensen [2000] argues that these two complementary operations can be carried out in various sequences, but identifies two commonly used sequences; a problem solving sequence and a design sequence. In the problem solving sequence, an analysis activity of an identified problem is followed by a synthesis, which will be an attempted solution to the original problem. In the design sequence, the synthesis activity creates innovation, which is subsequently analyzed and a specified innovative contribution is the outcome.

Joergensen [2000] argues further that these sequences may be embedded in each other. This is illustrated in figure 7 where a structure commonly used for research projects is shown. In this structure, an analysis is performed which results in the formulation of a diagnosis. Following the diagnosis is a synthesis which again is comprised by a sequence of synthesis and a subsequent analysis. The purpose of the first analysis can be to identify problems within a certain context and identifying if existing research has addressed these issues previously. The diagnosis then states where theory and methods must be developed to address these problems. In the synthesis activity, theories and methods are developed according to the shortcomings identified in the diagnosis and finally these new contributions are analyzed (by tests, comparison, implications, perspectives, etc.). The outcome of the process is the new research results.

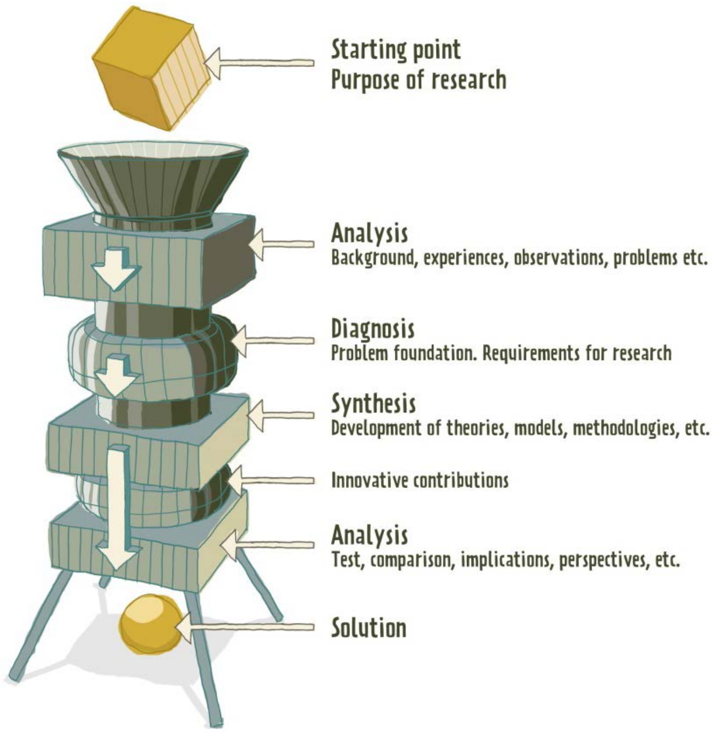


Fig. 7. *Methodical procedure commonly used for research and development projects [Joergensen, 2000].*

The structure outlined in figure 7 has been widely utilized in this project. Considering the project as a whole, the activities in the beginning of the project period has been identification of key issues regarding theories regarding assessment and measurement and regarding sustainability. Further, is has been about evaluation of which theories are applicable and which are not. This work was performed to make a diagnosis to provide outset for creating the main contributions from this project.

The synthesis of this project, i.e. the development of framework, evaluation criteria and new knowledge for assessment and measurement in mass customization, and sustainability and mass customization, is comprised by the work documented in the papers illustrated in the lower three boxes in figure 7. Each paper represents an isolated issue found in the diagnosis and this issue is processed as a synthesis. Hence, each issue has its individual outset but with the same background (the top analysis box). The thesis summary represents the final two boxes (contribution and analysis), i.e. the compiled results (chapter 5 and chapter 6) and discussion (chapter 7). As part of the final analysis, the significance of each metric selected in paper 5-9 has been analyzed against performance according to the related problem (the three capabilities). The contribution from paper 1 – 3 has been verified against end-of-life strategies in sustainability in new developed models and tables.

4.4 Research Limitations

In the research work with mass customization and sustainability, there have been natural limitations. Hence, domain knowledge within sustainability is primarily gained from the literature study. Working with sustainability requires multiple forms of expertise and the prerequisites for this project did not encompass any expert sustainability knowledge. The limitation has been analyses, diagnoses, and syntheses, which could be withdrawn from scientific papers at a system level comparable with the rest of the work. Hence the sustainability domain is widespread in many directions and the research and review for analysis has been delimited to scientific papers within product design and product design approaches.

5

Results and Contributions Assessment and Measurement

This chapter presents the results and contributions in assessment and measurement in relation to mass customization. It has a short introduction presenting the paradigm set for this part and a table presenting the metrics as an overview. Hereafter, three sections with a presentation of evaluation criteria's followed by a comprehensive presentation of each metric. Finally, metrics with relationships are presented.

Three fundamental capabilities in mass customization have been analyzed for key performance indicators during literature reviews and explorative research. To support this work each capability has been analyzed to establish evaluation criteria sets for each of the three capabilities. Because of the different nature of the capabilities, no common evaluation criteria set have been established. The evaluation criteria sets have been chosen on individual basis for each of the three capabilities, with two goals in mind 1) they must be measurable; otherwise they are per definition not metrics and 2) the required data should preferably be readily available in the company or should be easily obtainable.

Each of the included papers 6, 7 and 8 has en comprehensive presentation of potential metrics for each of the three capabilities and based on the evaluation criteria's there have been made a selection of metrics. Each metrics value has accordingly been verified for valuable information about the capability. These selected and verified metrics are presented as an overview in figure 8, followed by a walk-through of the metrics one by one, with name, equation (if existing) and a verification of how the metrics value can assist assessment and measurement in the specific capability.

5.1 Choice Navigation

In Choice Navigation the evaluation criteria set have been established with introduction of three sets and their intersections (see figure 9). Solution Space (SS), products and variants developed by the company, Customers Demanded Variety (CDV), ex-

Metrics		RPD	CN	SSD
Aggregate solution space profitability	ASSP			■
Profitability per Product Family	PFP			■
Negative Configuration Variable Profitability	NCVP			■
Skewness of the distribution of Profitability	CVPS			■
Used Variety	UV			■
Configuration Variable Utilization Percentage Variance	CVUPV			■
Mean Configuration Variable Utilization Percentage	MCVUP			■
Customers Repurchase Rate	RR		■	■
Configuration abortion rate	CAR/CA		■	■
Multiple Use	MU			■
Modules communality	MCM			■
Rate of which new configuration attributes are introduced	RNCA			■
Rate of eliminated configuration attributes	RECA			■
Average lead time for configuration variable changes	ALCVC			■
Differentiation Point Index	DPI	■		
Setup Index	SI	■		
Quality of Order Reception	QOR	■		
Number of different modules manufactured per process	NMP	■		
Degree of manual labor	DML	■		
Percentage point increase in process variety	PVI	■		
Capacity expense increase when introducing a new option	CAPIV	■		
Time to introduce a new option in the manufacturing system	TIV	■		
Cost of introducing a new option in the manufacturing system	CIV	■		
Customers Return Rate	RTR		■	
Customers Churn Rate	CR		■	
Customers Complaints Rate	COR		■	
Seller Order Cancellation rate	SOCR		■	
Seller Order change rate after purchase	SOCRAP		■	
Customer Order Cancellation rate	COCR		■	
Customer Order change rate after purchase	COCRAP		■	
Configuration sales rate metric	CSR		■	

Fig. 8. *Metrics found in research collected in one table, for assessing mass customization*

pressing customers' needs, and finally Customers Configuration (CC), an expression of the configuration actually done by the customer (or sales personal).

Analyzing figure 9, intersections B and C are consequences of a mismatch between the actual demand and solution space, where B implies variety which is part of the solution space but has no demand thus potentially implying unnecessary complexity costs. C implies a demand for variety that is not met by the current solution space and which may indicate an intersection where the development of the solution space could increase sales. The D intersection is seemingly less interesting in terms of choice navigation, since they relate primarily to the capabilities within solution space development.

In intersection D the customer configures a product that does not meet the demand nor is it contained in the solution space. This is not a typical situation but is nevertheless undesirable, and would likely be indicated by the customer abandoning the configuration. In intersection E, there is a match between the variety offered by the company and the customer demand; however the customer does not configure the product. This is likely a result of a user interface unable to guide the customer satisfactory through the configuration process. Intersection F indicates configuration, which match a customer demand, but is outside the actual solution space, i.e. a product that can be configured but not produced, which is also highly undesirable. Finally, in intersection G the customer configures a product that is within the solution space but does not meet the demand thus resulting in a customer disappointment.

CONFIGURATION ABORTION RATE METRIC (CA)

$$CA = \frac{N_a}{N_p} \quad \begin{array}{l} CA: configuration\ abortion\ rate\ metric \\ N_a: number\ of\ aborted\ configuration\ processes \\ N_p: number\ of\ logins\ (started\ configurations) \end{array}$$

source: [Blecker et al., 2003a]

The CA metric describes how frequently customers or sales people choose to abort a configuration which has been initiated due to whatever reason. A high CA value can be used as an indication, for intersection E (see figure 9), since customers that cannot configure a product to meet their requirements will likely abandon the configuration.

CUSTOMERS RETURN RATE METRIC (RTR)

$$RTR = \frac{number\ og\ returned\ products}{number\ of\ delivered\ products}$$

source: [Piller, 2002]

The RTR metric describes how often customers return a product to the company after receiving it due to e.g. disappointment in the product.

In this case, customers realize that the configured product does not meet requirements, after it is received. In this case the customer may return the product, which then is indicated by RTR. High RTR value indicates information about intersection G, an area within solution space but no customers' need (see figure 9).

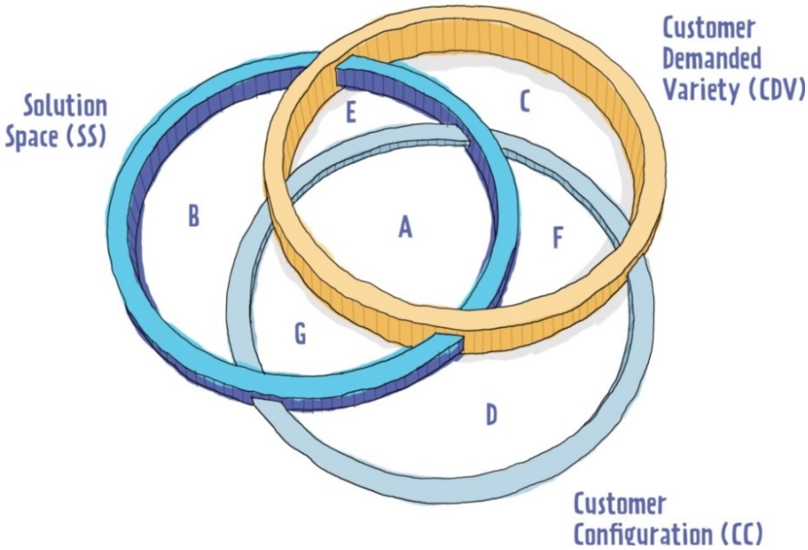


Fig. 9. *Evaluation criteria's for Choice Navigation*

CUSTOMERS CHURN RATE METRIC (CR)

$$CR(\Delta T) = \frac{NOLC(\Delta T)}{NOC(\Delta T) + NONC(\Delta T) - NOLC(\Delta T)}$$

$NOLC$: $number\ of\ lost\ customers\ at\ \Delta T$
NOC: $number\ of\ customers\ at\ T$
$NONC$: $number\ of\ new\ customers\ at\ \Delta T$

source: [Sterne, 2003]

The CR metric describes the relationship between new customers and lost customers. High value of CR indicates information about intersection G, an area with solution space but no customers' need (see figure 9).

CUSTOMERS REPURCHASE RATE METRIC (RR)

$$RR = \frac{repurchase\ through\ existing\ customers\ (\Delta T)}{number\ of\ new\ customers\ (\Delta T)}$$

source: [Piller, 2002]

The RR metric describes how often products are repurchased, or how often customers return to purchase another different product. A low value of RR indicates information about intersection G, an area with solution space but no customers' need (see figure 9).

CUSTOMERS COMPLAINTS RATE METRIC (COR)

$$COR = \frac{number\ of\ complaints\ (\Delta T)}{number\ of\ deliveries\ (\Delta T)}$$

source: [Blecker et al., 2003a]

Similar to the CR metric, the COR metric describes how often customers complain over a product they have purchased after receiving it. A high value of COR indicates information about intersection G, an area with solution space but no customers' need (see figure 9).

SELLER ORDER CANCELLATION RATE (SOCR)

$$SOCR = \frac{number\ of\ orders\ cancelled\ by\ seller}{number\ of\ placed\ orders}$$

source: [Nielsen et al., 2013]

The metric SOCR can have several reasons; one could be, customers configure products which are within the customer demanded variety but outside the solution space, i.e. a product is configured which cannot be delivered. This would likely result in the order being cancelled by the company, since it cannot be manufactured. High values of SOCR would then indicate configurations within intersection F, an area with customers need but no solution space (see figure 9).

SELLER ORDER CHANGE RATE AFTER PURCHASE (SOCRAP)

$$SOCRAP = \frac{number\ of\ orders\ changed\ by\ seller}{number\ of\ placed\ orders}$$

source: [Nielsen et al., 2013]

If a configuration is inside customer demand variety but outside solution space, an alternative to cancellation would be that the company will change the configuration to fit within the solution space by e.g. upgrading the product. High values of SOCRAP would then indicate configurations within intersection F (see figure 9).

CUSTOMER ORDER CANCELLATION RATE (COCR)

$$COCR = \frac{number\ of\ orders\ cancelled\ by\ customer}{number\ of\ placed\ orders}$$

source: [Nielsen et al., 2013]

In this case, the customer configures a product, which is within solution space but does not correspond to the customer's requirements and if the customer realizes that the product is not satisfactory prior to delivery, the customer may cancel the order. High values of COCR could indicate configurations within intersection G, an area with solution space but no customers' need (see figure 9).

CUSTOMER ORDER CHANGE RATE AFTER PURCHASE (COCRAP)

$$COCRAP = \frac{no.of\ orders\ changed\ by\ customer}{number\ of\ placed\ orders}$$

source: [Nielsen et al., 2013]

In this case, the customer configures a product, which is within solution space but does not correspond to the customer's requirements and if the customer realizes that the product is not satisfactory prior to delivery, the customer may alternatively change the order. High values of COCRAP could indicate configurations within intersection G, an area with solution space but no customers' need (see figure 9).

CONFIGURATION SALES RATE METRIC (CSR)

$$CSR = \frac{number\ of\ sold\ configurations}{number\ of\ started\ configurations}$$

source: [Nielsen et al., 2013]

CSR indicates when values are high, that most configurations lead to a sale, hence an indicator of being on target with choice navigation. Since configurations within intersection A should lead to a sale, then an increase in CSR would also indicate an increase in configurations within intersection A, the area which satisfy the customer, with solutions space and potential configuration opportunity (see figure 9).

5.2 Solution Space Development

A set of performance parameters has been introduced as evaluation criteria's for metrics in Solution Space Development, these parameters are presented in figure 10. Selected metrics for assessment and measurement of solution space development are as following:

AGGREGATE SOLUTION SPACE PROFITABILITY (ASSP)

$$ASSP = Total\ Sales\ income - Total\ manufacturing\ cost$$

source: [Brunoe et al., 2012]

The metric ASSP is a measure of how profitable the solution space is as a whole and should be measured over a period of time.

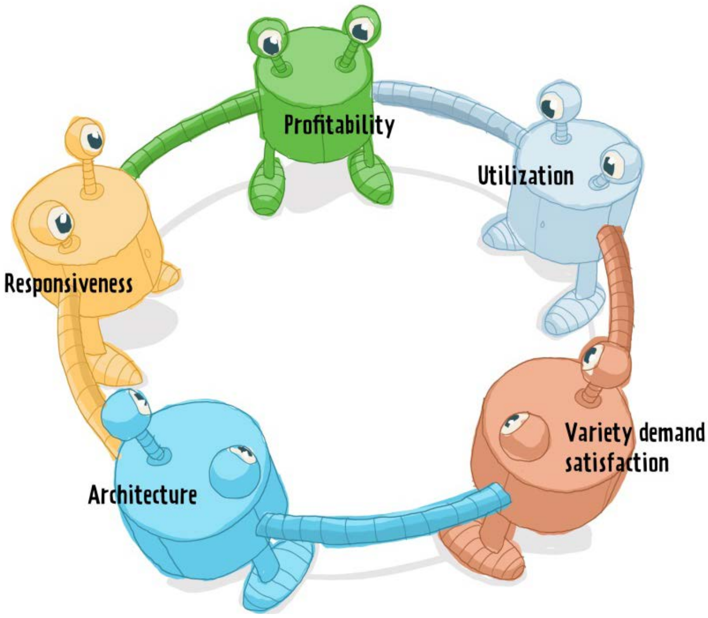


Fig. 10. *Evaluation criteria's for metrics covering Solution Space Development*

PROFITABILITY PER PRODUCT FAMILY (PFP)

$$PFP = Sales\ income\ from\ product\ fam - manufacturing\ cost\ for\ product\ fam$$

source: [Brunoe et al., 2012]

This metrics requires high data availability and detailed data about manufacturing cost. The metric can be used in comparison status as an indicator for profitability per product family over a period. Positive high values of PFP indicate profitable product family.

CONFIGURATION VARIABLE PROFITABILITY (CVP), NEGATIVE PROFITABILITY (NPCV), AND SKEWNESS OF THE DISTRIBUTION OF PROFITABILITY (CVPS)

CVP is a metric which is somewhat less trivial to determine. However, if historical configuration data is available with sales price and manufacturing costs registered for each configuration, it is possible to generate a linear model describing the variation in price and cost from the configuration variables using the methods described by Brunoe & Nielsen [2012]. From the significance and coefficients for each variable, it will be indicated if a specific configuration choice is profitable, e.g. a specific color. However assessing each variable may be useful in solution space development choices but less useful in assessing a company's overall capability, since it will consist typically of hundreds of records, corresponding to the number of configuration options. However, once the profitability for each option is calculated, the distribution of profitability's may be analyzed. What is interesting here is how many configuration variables (percentage) have negative profitability (NPCV). Obviously, this value should be as low as possible, and will indicate how well a company is able to develop only configuration choices, which are beneficial. Furthermore we propose a metric for the skewness of the distribution of profitability (CVPS). A positive value of CVPS will indicate that a few configuration variables are very profitable, whereas a negative value of CVPS would indicate that a number of configuration variables contribute significantly to a lower profitability. Specifically for these above mentioned metrics and because they are calculated based on algorithms no arithmetic equations have been included.

USED VARIETY (UV), MEAN CONFIGURATION VARIABLE UTILIZATION PERCENTAGE (MCVUP), AND CONFIGURATION VARIABLE UTILIZATION PERCENTAGE VARIANCE (CVUPV)

$$UV = \frac{Number\ of\ perceived\ variants}{Number\ of\ all\ possible\ variants}$$

source: [Brunoe et al., 2012]

UV metric addresses how well the solution space is utilized by the customers, i.e. how much variety is offered vs. how much does actually make sense compared to the customers' requirements. However, using this metric may be difficult in practice, since the number of perceived variants is not readily available. A more practical way of assessing the utilization would be to calculate the frequency by which each configuration variable is chosen by a customer. By dividing this by the frequency of which configurations are made in general, the percentage of configurations containing a certain configuration choice could be calculated, thereby describing the utilization of a certain configuration variable. If these percentages are analyzed statistically, the two metrics MCVUP and CVUPV can be derived. The value of these two metrics can provide insight into the magnitude and differences in frequency by which certain parts of the solution space are actually creating value for customers. Because they are calculated based on algorithms no arithmetic equations specific for MCVUP and CVUPV have been presented.

REPURCHASE RATE (RR)

$$RR = \frac{number\ of\ repurchases}{total\ number\ of\ purchases}$$

source: [Piller, 2002]

The metric RR describes to what extent customers repurchase a product, or to what extent customers return to the company to buy a different product. If customers repurchase products regularly, it is reasonable to assume that those customers have been happy with the variety and the product in general. Otherwise they would likely have chosen a competing product instead.

A high value of RR can be interpreted as an indicator for high customer satisfaction with the product offerings, including variety. Clearly, the RR does only make sense for products, which are purchased frequently, e.g. customized muesli or shirts, whereas products like cars or houses are purchased less frequently by the same customer, rendering this metric irrelevant.

CONFIGURATION ABORTION RATE (CAR)

$$CAR = \frac{number\ of\ aborted\ configurations}{number\ of\ initiated\ configurations}$$

source: [Blecker et al., 2003a]

The value of CAR (same as CA metric presented in chapter 5.1) can also be a measure of how satisfied the customers are with the offered variety. If a customer initiates a configuration and is not able to select the desired product properties, and is thus unsatisfied with the offered variety, that customer is likely to abandon the configuration and purchase a competing product. Hence, a high abortion rate could indicate that customers are dissatisfied with the offered variety and vice versa.

MULTIPLE USE (MU)

$$MU = \frac{NV}{NM}$$

source: [Gonzalez-Zugasti et al., 2001]

The value of MU metric indicates how many modules are required to produce all variants within the solution space [Ericsson & Erixon, 1999]. NV is the number of product variants required by customers and NM is the number of different modules required to build all variants in the product portfolio. While number of different modules should be easy for any company to determine, the number of variants required by customers is less trivial.

MODULES COMMONALITY METRIC (MCM), PARTS COMMONALITY (PC)

$$MCM = \frac{Number\ of\ common\ modules}{Total\ Number\ of\ different\ modules}$$

source: [Blecker et al., 2003a]

The MCM [Kaplan & Haenlein, 2006] is a measure of how many modules are common to all variants relative to the total number of different modules. Generally a higher MCM value will indicate more efficient product architecture, since higher commonality will usually imply lower manufacturing and development costs.

$$PC = \frac{Number\ of\ common\ parts}{Total\ Number\ of\ different\ parts}$$

source: [Blecker et al., 2003a]

PC [Kaplan & Haenlein, 2006] is used to measure the relationship between common parts and the total number of different parts in the same way as the MCM. A high PC value also indicates an efficient product architecture since that would imply higher purchasing volume for each different part further implying lower purchasing costs.

RATE OF WHICH NEW CONFIGURATION ATTRIBUTES ARE INTRODUCED (RNCA), RATE OF ELIMINATED CONFIGURATION ATTRIBUTES (RECA), AND AVERAGE LEAD TIME FOR CONFIGURATION VARIABLE CHANGES (ALCVC)

RNCA [Brunoe et al., 2012] is determined by summing up the number of added configuration choices during a certain period. Similarly, the value of RECA can be measured [Brunoe et al., 2012]. A high RNCA value indicates that a company frequently introduces new options for customers and would indicate that the company reacts to a broad spectrum of changes in the market. A large difference between RNCA and RECA would indicate that the solution space is either growing or shrinking. A steadily growing solution space could indicate a problem, since the company may be focusing on introducing new variety without doing “housekeeping” and eliminating options not needed anymore. This could result in unnecessarily increasing manufacturing complexity.

The two metrics described above describe the change rate of the solution space, but not the lead time for changes (ALCVC), which is also essential when competing in a rapidly changing market [Brunoe et al., 2012]. Specific for these above mentioned metrics and because they are calculated based on algorithms no arithmetic equations have been included.

5.3 Robust Process Design

To evaluate metrics in Robust Process Design, two viewpoints have been introduced and are indicated in figure 11.

- The ability to manufacture a variety of products within a fixed solution space, i.e. the current product portfolio / variety – *Robustness towards existing variety*
- The ability to adapt the manufacturing system to accommodate new variety, e.g. when the solution space changes due to new product options - *robustness towards new variety* This has a close relation to solution space development.

Both viewpoints of the capability are relevant; however they are not necessarily correlated. For example, a purely manual production is highly flexible towards new variety compared to a highly specialized and automated production, whereas the latter would probably be more efficient in manufacturing a predefined variety.

DIFFERENTIATION POINT INDEX (DPI)

$$DPI = \frac{\sum_{i=1}^{n} d_i v_i a_i}{n d_1 v_n \sum_{i=1}^{n} a_i}$$

v_i: #of different exiting in process i
n: number of processes
v_n: final number of varieties offered
d_i: average throughput time from process i to sale
d_1: average throughput time from beginning production to sale
a_i: value added at process i

source: [Martin & Ishii, 1997]

It is generally acknowledged that a late differentiation point or customer decoupling point is an enabler for an efficient mass customization production, the DPI is a measure of how postponed the variant creation is in a manufacturing process. DPI indicates the postponement of variants and on the other hand how many manufacturing processes have to change due to product variety. The most postponed manufacturing setup is expected to support highly robust manufacturing processes and therefore a very good indicator of robust process design.

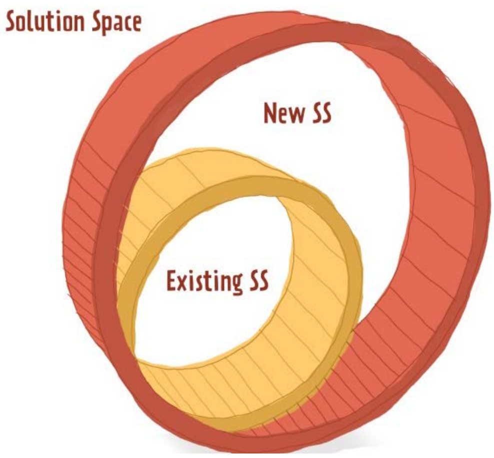


Fig. 11. *Evaluation criteria's for Robust Process Design*

SETUP INDEX (SI)

$$SI = \frac{\sum_{i=1}^{n} v_i c_i}{\sum_{j=i}^{v_n} C_j}$$

v_i: #of different exiting in process i
n: number of processes
v_n: final number of varieties offered
C_j: Total cost of Jth product
c_i: cost of setup at process i

source: [Martin & Ishii, 1997]

SI indicates how setup costs contribute to the overall manufacturing costs. The SI calculates the cost of setup of manufacturing processes compared to the total cost of a product. Since a high value of setup cost is an indicator of a low robustness, this indicator can contribute to the assessment of process robustness.

QUALITY OF ORDER RECEPTION (QOR)

$$QOR = \frac{\#\ of\ orders\ delivered\ on\ time\ \cap \#\ of\ orders\ with\ zero\ defects}{total\ \#\ of\ orders}$$

source: [Nasr & Thurston, 2006]

The metric QOR indicates how well the production performs in terms of on time delivery and the defect rate.

NUMBER OF DIFFERENT MODULES MANUFACTURED PER PROCESS (NMP)

$$NMP = \frac{\sum_{i=1}^{n} m_i}{n}$$

m_i: # of different modules manufactured at process i
n: : # of different processes

source: [Nielsen & Bronoe, 2013]

NMP gives a measure of the average number of modules manufactured in the different manufacturing processes. A higher value of NMP will indicate robust processes, since each process will be able to manufacture more different modules and thus a higher number of end variants.

DEGREE OF MANUAL LABOR (DML)

$$DML = \frac{\sum_{i=1}^{n} \frac{lc_i}{tc_i}}{n}$$

lc_i: labour cost for manucaturing product i
tc_i: total cost of manufacturing product i
n: #of different products

source: [Nielsen & Bronoe, 2013]

The metric DML can be used as an indirect indicator of process robustness, since a low value of DML indicates less need for manual processing, which again indicates that the non-manual manufacturing processes are able to supply a high variety.

PROCESS VARIETY INCREASE (PVI)

$$PVI = \frac{\sum_{i=1}^{n} p_i}{n}$$

p_i: # of new processes introduced for product option i
n: #of new product options in the period

source: [Nielsen & Bronoe, 2013]

PVI indicates how much the variety of manufacturing processes increases when a new product option or product is introduced in the manufacturing system. The PVI metric, calculated as an average during a period in time. A low value of PVI will indicate a high robustness since this implies that few new processes need to be introduced, when a product option is introduced and thus that the existing processes can accommodate new product variety.

CAPACITY EXPENSE INCREASE WHEN INTRODUCING A NEW OPTION (CAPIV)

$$CAPVI = \frac{\sum_{i=1}^{n} capi_i}{n}$$ $capi_i$: Percentual CAPEX increase from introducing product option i
n: #of new product options in the period

source: [Nielsen & Bronoe, 2013]

In addition to the PVI metric, the CAPIV is introduced. This is done since a high value of PVI does not necessarily can be compared with high cost, given a new process is implemented on existing flexible equipment. The CAPIV metric, also calculated as an average over a period of time.

TIME TO INTRODUCE A NEW OPTION IN THE MANUFACTURING SYSTEM (TIV) AND COST OF INTRODUCING A NEW OPTION IN THE MANUFACTURING SYSTEM (CIV)

$$TIV = \frac{\sum_{i=1}^{n} ti_i}{n}$$ ti_i: time from product design finish to manufacturing system ready
n: #of new product options in the period

source: [Nielsen & Bronoe, 2013]

$$CIV = \frac{\sum_{i=1}^{n} ci_i}{n}$$ ci_i: cost of introducing product option i
n: #of new product options in the period

source: [Nielsen & Bronoe, 2013]

The time and cost to introduce new product variety are also important metrics to assess process robustness, since robust processes will imply low cost and fast introduction of new product variety. The metrics Time to introduce a new option in the manufacturing system (TIV) and Cost of introducing a new option in the manufacturing system (CIV).

5.4 Metrics Relationships

Because identifying relationships between capabilities has not been part of hypothesis or research questions it has not problematized or analyzed nor been presented as part of any paper even though relationship was identified in concluding remarks in paper 8 and paper 9. Subsequently analysis based on figure 8 has identified at two metrics with relation more capabilities. These two can be recognized in figure 8 as RR (customers Repurchase Rate) and CAR (Configuration Abortion Rate). This identification verifies that relationships between capabilities exist. An interesting observation not in relation to any research question in the thesis or covered by any paper included, but in relation to chapter 8 (further research), important to have verified. Further it seems interesting to analyze if such relationship between capabilities of these metrics, adds further information in assessment and measurement of mass customization.

From the individual evaluation of metrics it can be found that output values from the metric RR can be interpreted with different results depending whether the value are evaluated in solution space development capability or in choice navigation capability – a high value of RR may in solution space development indicate good customer satisfaction, on the other hand in choice navigation a low RR value may indicate that our solution space does not satisfy our customers' demands.

The analysis discloses that high values of metric CAR can be understood as an indication of dissatisfaction with offered variety or that the configurator simply does not configure the customer demand, on the other hand a low value of metric CAR could indicates customer satisfaction or configuration of solutions space and customer demand is possible.

Both of the above examples of metrics indicate potential relationships across capabilities and potential differentiated information based on the metrics value is expected.

6

Results and Contributions Sustainability

This chapter presents the contributions and results completed from work with mass customization and sustainability and is documented in papers 1, 2 and 3, included in this thesis. The chapter is structured in a main part presenting the paradigm set in the research and two sections with close loop supply chains and product modularity.

To address the issue of how mass customization performs in terms of sustainability compared to other manufacturing paradigms such as mass production, an analysis of product life cycles was performed. To perform this analysis, mass customization and mass production was compared in the distinct steps of a generic product life cycle, being 1) Production, 2) Use and 3) End-of-Life.

Within the first two areas, production and use, the analyses are structured on the basis of concepts, which are characteristic for mass customization production and products. More specifically, the factors described by Berman [2002] and Maccarthy [2003] have been reviewed and those, which were found to have relevance for this study, have been included: 1) Product Modularity, 2) Process Variety, 3) Distribution Channels, 4) Improved fit with customer needs & 5) Product functionality customization. Furthermore, concepts, which have their origin in sustainability research, have been identified through literature studies.

The concept of reducing energy consumption, which is essential in eco design as well as life cycle thinking is included as well [Kørnøv et al., 2005]. In the End of life stage, a number of end of life strategies identified by Rose [2000] are included in the elements which are analyzed: 1) Energy efficiency, 2) Reuse, 3) Service, 4) Remanufacturing, 5) Recycling and disposal.

The results of the analysis performed are summarized in figure 12. As it can be seen from this illustration there are several relations between the elements of mass customization and environmental sustainability that indicate that mass customization does have an effect on the sustainability of a product. In figure 12, the cylinder in the center represent concepts, which are typically addressed by researchers and practitioners within mass customization, whereas the rings in the outside center represent the elements of sustainability that were found to have a relation to mass customization. Eight positive relationships and six negative relationships were identified; however these numbers cannot be used for concluding that mass customization is more sustainable than mass production, since these relations are not unambiguously quantifiable, since they can only be quantified for specific products, as different products will have different environmental impacts. What is also interesting is that few elements of mass customization potentially have both negative and positive effects on sustainability compared to mass production. One example of this is the individual distribution, which can have both negative and positive impact on the energy efficiency during distribution.

The analysis concluded that the assessment of whether mass customized products are more or less sustainable than similar mass produced products will depend entirely on individual product characteristics. Consider two completely different products; an automobile and a piece of clothing. The environmental impact profiles of these two products are completely different. The automobile will consume much more energy throughout the use phase of its lifecycle than consumed during product phase, where-

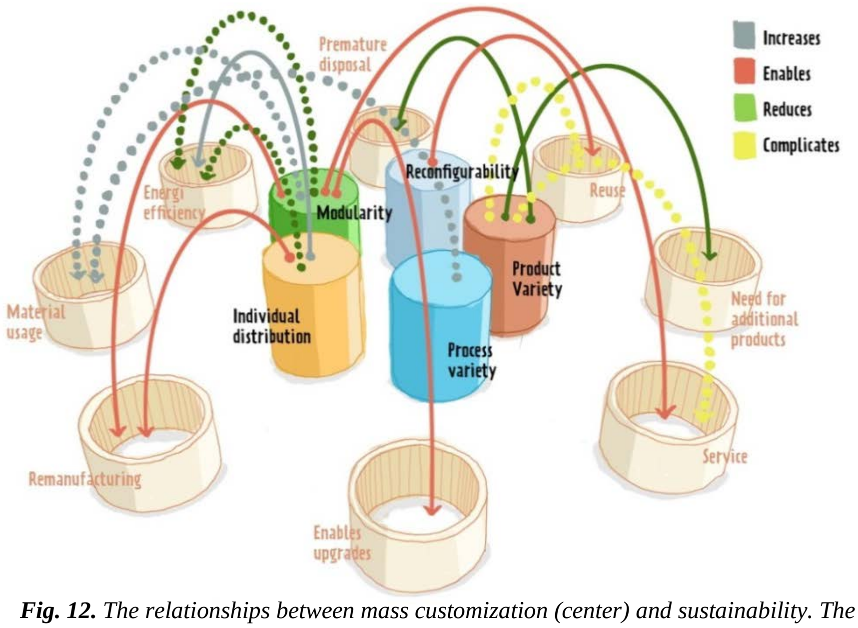


Fig. 12. *The relationships between mass customization (center) and sustainability. The dotted lines represent the identified relationships where mass customization potentially has a negative influence on sustainability compared to mass production opposite to the solid lines where mass customization can be expected to be more sustainable than mass production.*

as a piece of clothing will consume no energy during its lifecycle. Furthermore, an automobile is much more likely to be serviced to extend its life cycle and to be reused when its original purchaser disposes of it. Hence, the difference between mass customized and mass produced products will vary greatly between these two groups of products.

From the results of the analysis, there is no indication that mass customization should have the potential to be less sustainable than mass production. The results presented can thus be used as guidelines for how to address sustainability issues in mass customization by pointing out areas where mass customization is different from other business strategies, thereby assisting in tailoring strategies for becoming more sustainable.

6.1 Closed Loop Supply Chains for Mass Customization

In order to create sustainable products, the concept of closed loop supply chains is

	Advantages	Disadvantages
Reuse	Re-configurability enables customazation to new user	Poor fit to diverse customer demands
Service	Modularity enables replacement of defective modules	Product variety increases variety of spare parts
Remanufactoring	Modular products enables component replacement Product platform architecture enables remanufacturing of modules common to one product family	Product variety in EOL product supply complicates demand planning Custom manufactured components are unsuitable for remanufacturing
Recycle with disassembly	Easier disassembly due to modular product architecture	Difficult to optimize or automate disassembly process due to product structure variety
Recycle without disassembly	None	None
Disposal	None	None

Fig. 13. Overview of product end-of-life strategies and implications for mass customization products compared to mass produced products

essential. A closed loop supply chain is a combination of a reverse supply chain and a traditional forward supply chain where the components or materials retrieved from products in the reverse supply chain are used to manufacture products for the forward supply chain, thus closing the materials loop [Rose, 2000]. Furthermore, shorter closed loop supply chains will usually imply a higher sustainability performance, i.e. in the future companies, mass customizer as well as other companies, will be faced with the challenge of closing the supply chains and making the loop as short as possible. Rose [Rose, 2000] introduced a hierarchy of end-of-life strategies, where each strategy corresponds to a certain closed loop supply chain setup. The hierarchy has the following levels: 1) reuse, 2) Service, 3) Remanufacture, 4) recycling with disassembly, 5) recycling without disassembly and 6) disposal. This implies for example that reuse is preferred over service as it requires fewer resources, and as well as recycling is preferred over disposal for obvious reasons.

An analysis has been performed in this project to identify, which challenges arise when closing the material loop for mass customized products and more specifically , which challenges arise in the different setups. In figure 13, an overview of the different end-of-life strategies and their implications for mass customization products, identified from the analysis, is presented. For the upper 4 levels a number of challenges exist which are specific to mass customization products, however a number of characteristics of mass customization products also provide benefits for the different closed loop supply chain end-of-life strategies compared to non mass customization products. Finally, no differences were found for the lower two end-of-life strategies between mass customization and non mass customization products. To determine how the challenges of the end-of-life strategies are different across different product types, case studies were conducted, including a generic mass customization product, an office furniture manufacturer, a computer manufacturer and the automobile industry. The case studies showed significant differences in the approaches towards closing the supply chain loop, which are due to differences in the characteristics in products.

Utilizing closed loop supply chains has a great potential in achieving a higher degree of product sustainability, since this will reduce the amount of waste produced as well as reducing the demand for raw material production and energy consumption. Although only a minor part of mass customizers are utilizing closed loop supply chains, the case studies have shown that it can be an attractive business proposition to e.g. remanufacture products and resell them.

6.2 Product Modularity and Sustainability

It is commonly acknowledged that the usage of modular product architecture is an efficient way of creating the product variety necessary in mass customization [Ericsson & Erixon, 1999; Tseng & Jiao, 1996; Ulrich & Eppinger, 2003]. Furthermore, the usage of modular product design has proven to have a number of long term positive effects on product development as well as manufacturing and logistics [Pine, 1993]. Since modularity is an essential building block of mass customization, an analysis has been conducted to investigate to what extent modularity promotes sustainability. This analysis was carried by first performing a literature review and compiling a list of the commonly used module drivers and subsequently evaluating how these module drivers are related to basic ECO-design rules found in Karlsson & Luttrop [2006]. Module drivers are according to Ericsson and Erixon [1999] the driving forces behind why a company would want to develop modular products. Module drivers are so to speak the positive effects of modularization seen over the entire life cycle of a product from product design through manufacturing, usage and disposal. The module drivers were divided into five categories: 1) Localization of changes in product, 2) Variety and standardization, 3) Production 4) After sales and 5) Product development. The ECO-design rules used to evaluate the relationships are adopted directly from Luttrop & Lagerstedt [2006]: 1) Do not use toxic substances and utilize closed loops for necessary but toxic ones. 2) Minimize energy and resource consumption in the production phase and transport through improved housekeeping. 3) Use structural features and high quality materials to minimize weight in products, if such choices do not interfere with necessary flexibility, impact strength or other functional priorities. 4) Minimize energy and resource consumption in the usage phase, especially for products with the most significant aspects in the usage phase. 5) Promote repair and upgrading, especially for system-dependent products (e.g. cell phones, computers and CD players). 6) Promote long life, especially for products with significant environmental aspects outside of the usage phase. 7) Invest in better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear, thereby ensuring reduced maintenance and longer product life. 8) Prearrange upgrading, repair and recycling through access ability, labeling, modules, breaking points and manuals. 9) Promote upgrading, repair and recycling by using few, simple, recycled, not blended materials and no alloys. 10) Use as few joining elements as possible and use screws, adhesives, welding, snap fits, geometric locking, etc. according to the life cycle scenario.

The analysis showed that all module drivers are directly influenced by the ECO-design rules. Furthermore it showed that all but one ECO-design rule influence one or more module drivers. There is a major difference in the nature of relations and the number of module drivers which a certain ECO-design rule influences.

Product development involves trade-offs between different module drivers and it will thus not be possible to establish an architecture, where the product is designed optimally for each individual module driver, and product designers must choose which module drivers to focus mostly on and which to focus less on. By doing this, it is the intention to achieve the best trade off or a global optimum rather than sub optimizing for certain drivers. This task will become even more complex, when taking into account the ECO-design rules. However, clarifying the relations and taking these into consideration when developing products will support the transition to greener products since the module drivers according to these results can in fact support ECO-design.

From a mass customization point of view, a customer looking for a sustainable product would more easily be able to customize ”a green product”, because configurators can assist the customer in making suitable choices. This is possible because options can be presented in accordance with ECO-design rules incorporated in module specifications.

7

Discussions and Conclusion

This chapter is divided in four sections. The first section with discussions and conclusions, including diagnoses, analyses and results originating from hypothesis 1 and hypothesis 2 and associated research questions, in relation to assessment and measurement of mass customization. The second section with discussions and conclusion originating from hypothesis 3 and its related research questions, in the work with mass customization and sustainability. The third section indicates further research potential in this domain. Several roads to follow for further research can be identified based on the research and results presented in the thesis. At least three roads have been identified as potential research areas to follow in mass customization assessment and measurement. The last section is an overall conclusion.

7.1 Assessment and Measurement

The three different evaluation criteria are used in the detailed analyses of the three capabilities could imply some potential discrepancy in the validity of the metrics as suggested. The three different evaluation criteria have its origin in different preambles in analyses and diagnostics of the three capabilities as one motivation. Another one can be related to the progress of the project in fact as explained in chapter 5 Methods illustrated in with figure 7 – sums of knowledge opens up for new analysis and diagnoses. In chapter 8, it is suggested that further research could involve "model of relationships" which implies an additional full circle analysis of all metrics based a solitary evaluation criteria set. The metrics presented in the thesis are not intended to be changed in such additional research, but potential additional metrics could be the results of such aligned approach. Based on the workflow, analysis, diagnoses and synthesis, it is recommended that any further research in metrics should have its outset in an evaluation and recommendation regarding which of the three criteria should be used if not a new should be developed. It is evident that the any industrial application assessing or measuring mass customization based on these metrics entails certain requirements related to data availability and quality. However, most mass customization companies have already systems in place, which are very likely to contain the data required for calculating the metrics presented in the thesis.

There are strong relations between these three capabilities, and phenomena experienced in a company cannot necessarily be attributed to only one capability. If for instance the profitability of the solution space changes, it may be difficult to tell, if this change can be attributed to changes in the solution space, changes in the manufacturing processes lowering manufacturing costs or changes in choice navigation leading customers to choose products sold at a greater price.

One example is the metric configuration abortion rate, which is argued indicates how well choice navigation is implemented. However, the configuration abortion rate will be strongly influenced by the solution space, i.e. how well the offered variety matches the demanded variety. In future research the relationship between the capabilities should be established and the links between all three capabilities need to be analyzed. Furthermore, the relations between metrics performance and specific methods should be addressed so that an assessment could point out not only what a company should do to improve but also how.

When performing an assessment and interpreting the values of the metrics, the interpretation should take into account the product type. Also when benchmarking, companies manufacturing different products cannot necessarily be compared directly. The reason for this is that several metrics are based on the customers' actions, and these actions will depend on the product type. For example a customer buys a customized car compared to a customized bag of muesli, the customer would probably then be more likely to complain or return the car if it has a wrong color compared to the muesli, if a wrong ingredient has been added. In that case, the difference would be due to the difference in cost of the products. Furthermore a metric like the repurchase rate makes more sense for some product types than others. For example, customers are likely to repurchase muesli more often than cars. So this metric would depend on to what extent a product can be characterized as a consumable or a durable, and in case it is a durable, how long the life cycle is.

In order to support the development of production in mass customization, metrics are needed in order make performance measurement, assessment and benchmarking. To establish these metrics, relevant literature has been reviewed and several applicable metrics has been identified. Further metrics have been defined in areas where no sufficient metrics could be identified in literature.

In relation to research in mass customization it is the intention to apply these metrics in different types of mass customization companies to analyses what distinguishes successful mass customizers. It is the intention that these metrics can be used in mass customization companies for different purposes. One purpose is benchmarking against "best practice" mass customizers, in order to identify areas with the greatest potential for improvement. Another purpose is to use these metrics as key performance indicators which are continually calculated to monitor performance to continuously improve.

It has been proven that it is possible to establish a framework for assessment and measurement of mass customization, which was hypothesis 1. Answering the research questions following hypothesis 1 lead to identification that this framework can be established based on three fundamental capabilities as proposed by Salvador et al. [2009]. It has also been proven that it is possible to establish a set of metrics, which are able to assess and measure these three fundamental capabilities in mass customization. These metrics are a mix of previously suggested by other researchers and some are developed during this project. This part of contributions responds to hypothesis 2 and its research questions.

7.2 Sustainability

In the research of mass customization and sustainability, limitations have been made right from the start of this part of the project, mainly because expert knowledge within sustainability was not present. On the other hand, working with sustainable product design rules, it was found that sustainable thinking has similarities with engineering design rules. This recognition has been the outset in the work with mass customization and sustainability and the very early assumption leading to the hypothesis 3 that mass customization product design approach will match the need for being sustainable, or at least not be a hinder or becoming sustainable, and on the other hand being green do not necessary hinder that you can become a mass customizer.

The research results presented in the thesis and the papers included proves that it is possible at the same time being both a mass customizer and sustainable. Results indicates that sustainable product design rules like 10 Golden Rules [Luttropp & Lagerstedt, 2006] or Cradle-to-Cradle rules [McDonough & Braungart, 1992; McDonough et al., 2003] works along with design rules for modularity the enabler for mass customization. Furthermore results indicate that mass customized products do not hinder sustainable thinking adopting closed loop supply chains. Finally results indicate mass customization approach neither complements nor clashes with typical strategies for handling end-of-life products.

7.3 Further Research

A model of the relationships between the metrics across capabilities has to be established, along with identification and verification of causal relations. The metrics presented in the thesis has to be tested and verified in such a model and potential “black holes” has to be identified and covered with additional metrics. This research is intended as the next theoretical step.

Industrial test and validation of the suggested metrics is essential task to perform. Several issues have to be addressed in such a test and verification setup. First, the expected availability of the data and source of data, which the research has been established on, has to be identified, tested and verified. Secondly, the stream of data and validity of the data has to be tested and examined, and finally verification and reliability of the metrics has to be calculated and verified. This research is expected as an industry related work.

Furthermore, research must go into development of methods and tools making it possible to introduce the metrics into industrial application. Concrete solutions on how to establish management dashboards with mass customization information, typically seen as business intelligence systems, should be developed. This research is intended to be done in collaboration with a major business intelligence system supplier.

Further research in mass customization and sustainability is suggested as collaboration with researchers in sustainable product designs, to test and verify the contributions from this thesis.

7.4 Concluding Remarks

Each paper represents an individual contribution to a scientific problem, and each paper can be read as is and the results can be used independently or in relation to the other papers. The papers have all been published through various scientific channels and each papers problem, analysis, diagnoses, synthesis and results have been reviewed, presented and discussed on peer basis. The initial scientific objective "*contribute to existing theory in the field of mass customization*" has been fulfilled with this thesis three papers in the sustainable domain and six papers in the domain of assessment and measurement, as well as the main and additional objectives to have been fulfilled too with the analyses and results presented.

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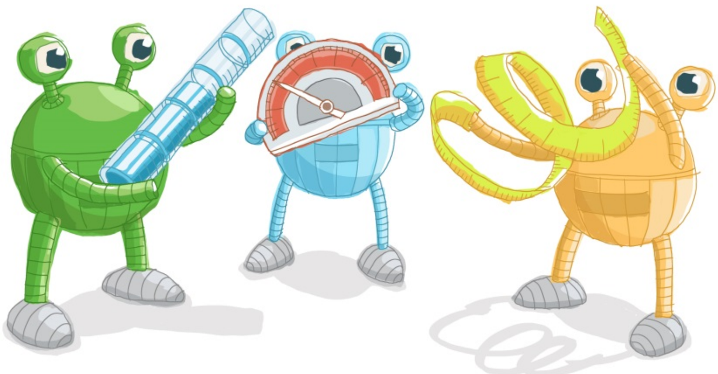
PART II

PAPERS



List of Papers

Paper 1

Supporting Sustainability and Personalization with Product Architecture

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Supporting Sustainability and Personalization with Product Architecture

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Abstract

Mass Customization, Personalization and Co-creation (MCPC) are continuously being adopted as a competitive business strategy. Consumers as well as governments are at the same time applying pressure on companies to adopt a more sustainable strategy, consumers request greener products and governments applies rules for reuse and more eco-friendly manufacturing. There are several possible factors which could indicate that MCPC would not unify the support for a strategy for sustainability however there are also factors which could increase the sustainability of product designed for MCPC.

Hence modularization is a driver for MCPC and earlier research with product architecture has indicated that modularization could support sustainability; further empiric work with the drivers for modularization with focus on sustainability and MCPC, will be presented in this paper. Several modularization methods and drivers are analyzed for support of sustainability and MCPC. It is concluded that several drivers for modularization can support sustainability.

1. Introduction

Mass Customization, Personalization and Co-creation (MCPC) are adopted as a competitive business strategy (Davis, 1989; Pine, 1999; Piller & Tseng, 2010; Salvador et al, 2009) . Within the domain of MCPC several sub disciplines such as variety, modularity, commonality, adaptability, flexibility, reusability, customisability, economies of scale, scope etc. are well known as areas of general interest and therefore also have great research interest.

Work has been done to set sustainability on top of list for governments, designers, engineers, manufactures, customer, etc.

Organisations in general, NGO's, private and business movements, costumers' organisation, are all a part of the stakeholders, who have addressed the sustainability domain. Much of this work has been used as an off-set for sustainability in general, as seen in Bruntland report (Hueting, 1990; Brundtland, 1987) and the Hannover principles (McDonough & Braungart, 1992) used as foundation for the Cradle-to-Cradle movement, and later The Ten Golden Rules (Luttropp & Lagerstedt, 2006).

Governments have set sustainability on top of the list, as information about environmental issues, behavioural education and with legislation, which requires manufacturers to address the issues of sustainability (Maxwell & Van der Vorst, 2003; Hall & Vredenburg, 2003; Lindhqvist, Thidell, Power, Hansen and Jensen. , 2011; Karlsson & Luttropp, 2006; SDC-UK. , 2011). On the other hand a request for sustainability is driven by costumers, which also leaves the manufactures with a need for fulfilling these requirements (Linton, 2005; Manzini & Vezzoli, 2003; Stegall, 2006; Klöpffer, 2003; Seuring & Muller, 2008).

These requirements of "sustainability" they cannot be solved solely looking at physical attributes like: product architecture, energy use, manufacture, logistics, and end-of-life handling (Stegall, 2006), but do need attention to the design process and design rules as well.

Comprehensive research has been done to find the rules(even "golden rules") (McDonough & Braungart, 1992; Luttropp & Lagerstedt, 2006; Anastas & Zimmerman, 2003; Bolton, 2010; McDonough & Braungart, 2002b; McDonough et al, 2003; McDonough & Braungart, 2002a; Ashford, 2002) for designing sustainable products. Models and methods have been presented from general form to specific methods to be used by designers, engineers and manufactures (Nidumolu et al, 2009; Byggeth et al, 2007; Waage, 2007; Sonntag, 2000).

This work will address a small portion of the practical work on sustainability in relation to MCPC. One enabler for MCPC is modularity (Pine, 1993; Tseng et al, 1996; Hvam et al, 2008; Ulrich &

Eppinger, 2003) and several approaches as drivers for modularity have been presented, some of those used in this research have been presented by Ulrich & Eppinger (Ulrich & Eppinger, 2003; Ericsson & Erixon, 1999) and Ericsson and Erixon (Ericsson & Erixon, 1999).

This paper will address and focus on (some) drivers for modularization in relation to sustainability.

1.1 Modularity

It is commonly acknowledged that the usage of modular product architecture is an efficient way of creating the product variety necessary in mass customisation (Tseng et al, 1996; Ulrich & Eppinger, 2003; Ericsson & Erixon, 1999). Furthermore, the usage of modular product design has proven to have a number of long term positive effects on product development as well as manufacturing and logistics (Pine, 1993). Numerous definitions of modular product architecture exist but in this context the definition of modular product architecture defined by (Ulrich & Eppinger, 2003) is adopted. This definition states that products with modular architectures have the following properties: 1) One module, being a part of the product implements one or few functional elements and 2) The interactions and thereby interfaces between modules are well defined (Ulrich & Eppinger, 2003). This applies to physical products and may to some extent also apply to digital products. However, digital products variety can also be implemented without usage of a physical modular architecture, since products can be customized by non-physical means. Ulrich and Eppinger (Ulrich & Eppinger, 2003) define three different types of modularity: 1) Slot modular architecture, 2) Bus modular architecture, and 3) Sectional modular architecture. In the sectional-modular architecture however all interfaces between modules are identical, implying that modules can be combined randomly and no module is common to all products in a product family. This is in contrast to platform based product families which are described in the following.

Modular product architecture is broadly defined often considered the opposite of integral product architecture, in which products are not logically divided in modules with clear interfaces (Joergensen, 2008). This architecture is typically chosen for performance reasons, when size is an important optimization issue or if the product is produced in a volume, where the accumulated variable costs exceed the savings from choosing modular architecture.

1.2 Defining a product architecture

The process of defining the product architecture is part of a product development process (Ulrich & Eppinger, 2003), where the decisions are made regarding the mapping between the products' function and its physical structure. Assuming a modular product architecture, the process is usually referred to as a modularization process. Typically this will take place in the early stages of a product development project, where the main characteristics and requirements have been defined, and the design work to some extent has been initiated. However, this task should be completed before the detailed design is started because it usually will have a high influence on the requirements for the detailed design. The mapping is performed according to so-called module drivers which will be described below.

1.3 Module drivers

Module drivers are according to Ericsson and Erixon (Ericsson & Erixon, 1999) the driving forces behind why a company would want to develop modular products. Module drivers are so to speak the positive effects of modularization seen over the entire life cycle of a product from product design through manufacturing, usage and disposal.

When choosing product architecture and choosing between modules, there will inevitable be a trade-off between the module drivers in achieving the decisive goal. In perceiving the lowest number of modules more parts and components will end up in one module to fulfil the functions needed.

How well is the match between a low number of modules in relation to sustainability and EcoDesign?

1.4 Sustainability, EcoDesign and product development

Sustainability has been set as a major focal point in designs and one generally recognized as approach to achieve this is EcoDesign (Luttropp & Lagerstedt, 2006). Product development with sustainability or re-usability as the individual goal for design or redesign has proven not to be the road to follow (Nidumolu et al, 2009). Sustainability has to be a strategic approach for companies with strategic goals specifically for sustainability (Stegall, 2006; Sonntag, 2000). With a firm strategic foundation for sustainability, companies can work through the process as key driver for innovation (Nidumolu et al, 2009). The 5 step approach presented by Nidumolu, et al (Nidumolu et al, 2009) shows the path, how most companies reach the strategic goals of sustainability.

Table 1 5 stages path to sustainability (Nidumolu et al, 2009)

Viewing Compliance as Opportunity
Making Value Chains Sustainable
Designing Sustainable Products and Services
Developing New Business Models
Creating Next-Practice Platforms

Other approaches can of course be followed and most approaches will follow roads which involve the product in its lift time, as Life Cycle Thinking(Thabrew et al, 2009) and Life Cycle Assessment (Curran, 1993); one could be the Cradle-to-Cradle (C2C) (McDonough & Braungart, 2002b; McDonough & Braungart, 2002a) approach introduced and commercialized by McDonough and Braungart during the last 15 - 20 years.

Following one or another strategic approach to sustainability, one inevitable step is designing product to fulfil requirements for sustainability.

The C2C has its set of specific rules and during the last decade, several methods how to decode C2C into specific designing methods has been presented (Maxwell & Van der Vorst, 2003; McDonough et al, 2003; McDonough & Braungart, 2002a).

In general, designing for sustainability has turned into the concept and term – EcoDesign. As seen for C2C several methods and rules of EcoDesign have been presented (Luttropp & Lagerstedt, 2006; Klöpffer, 2003; Byggeth et al, 2007; Waage, 2007; Knight & Jenkins, 2009). These methods and rules have commonly Product Life Cycle as the approach – C2C as the term indicates, the design should support re-usability, even more specific, the raw material in the Technosphere used for the product and the process should not degenerated over time (McDonough et al, 2003). The approaches to EcoDesign use a more broad view going from the Raw Material to End-of-Life (fig 1).

Fig. 1 The view of EcoDesign

For the latter analysis, the EcoDesign and The Ten Golden Rules (10GR) presented by Luttrop and Lagerstedt (Luttropp & Lagerstedt, 2006) are used. The 10GR has been used for the last 15 years and are chosen among others as an objectively generic approach. The 10GR are presented using the Luttrop and Lagerstedt (Luttropp & Lagerstedt, 2006) figure (fig. 2) and below citation.

Fig. 2 The Ten Golden rules for EcoDesign (Luttropp & Lagerstedt, 2006)

ONE Do not use toxic substances and utilize closed loops for necessary but toxic ones.
TWO Minimize energy and resource consumption in the production phase and transport through improved housekeeping.
THREE Use structural features and high quality materials to minimize weight .in products .if such choices do not interfere with necessary flexibility, impact strength or other functional priorities.
FOUR Minimize energy and resource consumption in the usage phase, especially for products with the most significant aspects in the usage phase.
FIVE Promote repair and upgrading, especially for system-dependent products. (e.g. cell phones, computers and CD players).
SIX Promote long life, especially for products with significant environmental aspects outside of the usage phase.
SEVEN Invest in better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear, thereby ensuring reduced maintenance and longer product life.
EIGHT Prearrange upgrading, repair and recycling through access ability, labelling, modules, breaking points and manuals.
NINE Promote upgrading, repair and recycling by using few, simple, recycled, not blended materials and no alloys.

TEN Use as few joining elements as possible and use screws, adhesives, welding, snap fits, geometric locking, etc. according to the life cycle scenario. (Luttropp & Lagerstedt, 2006)

1.5 Research objective and method

The objective of this research is to analyse the relationship between modularity and sustainability in terms of how the application of sustainable principles can impact the modularization process. This is translated into the research question:

How can the sustainability influence the decision regarding product modularity?

This question is answered using the following approach which outlines the remainder of this paper:

A review of the most commonly used module drivers is presented.

For each module driver it is evaluated how the use of The Ten Golden Rules of EcoDesign influences the significance of that particular driver.

The implications of how the application of the sustainable principles influences the product architecture are discussed.

2. Review of module drivers

Ericsson and Erixon (Ericsson & Erixon, 1999) identified a number of module driver while developing the method modular function deployment. These drivers are outlined in the table below, indicating drivers to the right and categories of module drivers to the left.

Table 2: Module driver as presented by Ericsson and Erixon (Ericsson & Erixon, 1999)

CATEGORY	MODULE DRIVER
Product development and design	Carryover
	Technology evolution
	Planned product changes
Variety	Different specification
	Styling
Production	Common unit
	Process and/or organization
Quality	Separate testing
Purchase	Supplier available
After sales	Service and maintenance
	Upgrading
	Recycling

Ulrich and Eppinger (Ulrich & Eppinger, 2003) identified a number of factors which are essential to consider when clustering product functions in chunks, which is their terms for defining the modularity. These factors translate directly into module drivers using the terminology of Ericsson and Erixon (Ericsson & Erixon, 1999). These factors are outlined in the following and are to some extent similar, however this will be addressed in the following and a complete list of module drivers will be presented. Table 2 outlines the module drivers presented by Ulrich and Eppinger (Ulrich & Eppinger, 2003).

Table 3: Module driver as presented by Ulrich and Eppinger (Ulrich & Eppinger, 2003)

Geometric integration and precision
Function sharing
Capabilities of vendors
Similarity of design or production technology
Localization of change
Accommodating variety
Enabling standardization
Portability of interfaces

In the following, the identified primary module drivers will be described in more detail. To join the different module drivers from Ericsson and Erixon (Ericsson & Erixon, 1999) and Ulrich and Eppinger(Ulrich & Eppinger, 2003), five categories are used: 1) Localization of changes in product, 2) Variety and standardization, 3) Production 4) After sales and 5) Product development.

2.1 Product development

The module driver geometric integration and precision is relevant in products where certain components need to be very carefully aligned for the product to function. Examples of this include cameras, where the optics and sensors need to be very carefully positioned to function correctly. By integrating such components in the same module, there is a lower risk of quality issues in the finished product, since assembly precision will not be an issue in the final assembly of the product. Geometric integration refers to cases where components need to be positioned next to each other or one is contained within another. This could for example be an axle and a bearing which would usually be included in the same module, because they cannot function separately.

Another module driver is function sharing. This refers to cases where two functions in a product can share some kind of sub-function. This module driver is widely applied in design of electronics, where certain functions may be implemented on the same circuit board to share functions like power supply, a micro-processor or cooling. By sharing a support function, the cost of developing producing that support function is saved and the size of the final product may be reduced.

In some product types, the portability of interfaces is an essential module driver. Components which have interfaces which are not easily portable will usually be beneficial to implement in one module. The portability of an interface is defined by how easy it is to place two components with a common interface apart from each other. Some specific types of interfaces are more easily portable than others. For example are electrical interfaces usually more portable than mechanical or force transmitting interfaces. As an example consider a car engine. The gearbox contains numerous mechanical force transmitting interfaces which cannot be transmitted over a distance and is thus implemented as a single module. The engine control unit contains several electrical interfaces to sensors on the engine. Since the electrical signals can easily be transmitted from sensor to engine control unit, these will not need to be implemented in one single module as for the gearbox.

2.2 Localization of changes in product

Module carryover refers to cases where some function in the product is not expected to change for a number of product generations. In these cases it is usually beneficial to cluster this function in a module since this module can be 'carried over' more or less unchanged to later generations of the product (Ericsson & Erixon, 1999). This implies that the cost of developing that module type will not occur in subsequent development projects using the module, leading to reduced development cost. Considering the example of a computer, module carryover would apply for a module like the power supply, which has a function that can be considered stable over time and will thus not need changes from one generation to another in the same pace as the CPU or hard drive, where technologies and customer requirements evolve much faster.

Technology evolution refers to parts of a product where a change can be expected which is caused by demand for new technology, the presently used technology becomes obsolete or opportunities regarding e.g. new materials are introduced (Ericsson & Erixon, 1999). As an example, consider a digital camera, where technological evolution is driven by the development of imaging sensors with more megapixels. If the imaging sensor as well as the electronics necessary to control the sensor is incorporated in a module with a standardized interface, the sensor technology can be updated without changing the rest of the product.

Planned product changes are similar to technology evolution, however, what drives these changes in the product is not technology but rather product changes, which are part of a product plan e.g. to provide new functionality to the customer. Although in some cases, this would imply using new technology as described above this is not always the case and the motivation for making the change is fundamentally different. One example of this is the way commercial aircraft manufacturers develop aircraft families. Much like a product platform, one variant (base model) of a new aircraft type is developed and introduced. Once this variant is in production, stretched or shortened versions are developed. This however can only be done if the original aircraft design is based on modules that allow the fuselage modules to be stretched without changing e.g. wing, tail or cockpit modules. By doing this the cost of developing variants of the aircraft is much lower than developing a completely new aircraft.

The benefits of implementing elements which are expected to change either due to technology evolution or planned product changes are very similar. By clustering these elements in one or a few modules, the change will be focused in that particular module and thus the rest of the product design may remain unchanged. Assuming that making engineering changes in fewer modules leads to lower cost, clustering elements expected to change will reduce development costs for subsequent projects.

2.3 Variety and standardization

Although contrasting concepts, in relation to modular products, variety and standardization are closely related.

It is widely acknowledged that modular product design is an efficient means to achieve a high product variety at low costs. The reason for this is that a product family designed with interfaces supporting exchange of modules may present the customer with a very large variety by combining even a small number of modules. One example of this is configurable cars, where a single model with options for e.g. engines, wheels, audio systems and interior styles can offer the customer billions of variants using a relatively low number of modules to choose from. Ericsson and Erixon (Ericsson & Erixon, 1999) have classified the variety into product specification and styling variety, where product specification refers to the actual functionality of the product, whereas styling only refers to the appearance.

The module driver common unit or enabling standardization is the idea of identifying a function which is required in a number of different products in a product portfolio, developing a module implementing this function and utilize it in all of these products. By doing this, development effort is saved, since the module needs only to be designed once, and economies of scale can be achieved in production with lower unit costs as a result (Ulrich & Eppinger, 2003; Ericsson & Erixon, 1999). Considering a family of different televisions, with different designs and sizes as an example, the tuner module will need to have the exact same function and can thus be implemented in a single standard module common to all televisions in that family.

2.4 Production

Establishing modules based on similarity in production technology can greatly reduce the manufacturing costs of a module. Consider a modular product requiring three different production technologies, which is available in three different manufacturing lines. If each module requires different manufacturing technologies, the module would have to be moved between manufacturing lines, increasing the lead time and manufacturing costs. Furthermore, certain manufacturing processes are incompatible, for example, metal welding a part which is moulded plastic is not possible since the heat from the welding would melt or burn the plastic.

In some cases it is necessary to perform tests of certain functions of a product, before the product is assembled. By doing this, faults will be identified and addressed at an earlier time in the value chain, and will lead to reduced costs of poor quality. In such cases, it may be beneficial to establish modules based on need for testing.

Vendor capabilities can also be a driver for establishing a module. If the development and manufacturing of certain functions in a product is outsourced to external partners, having those functions implemented in a single or few modules will allow easier specification of interfaces and reduced complexity in the assembly process. Furthermore, certain functions may be available from specialized suppliers as standard modules, which would remove development cost and reduce purchase costs as well. A well-known example of this is the Engine Control Unit (ECU) of a car. This unit is nearly always developed and produced by one of a few specialised suppliers of ECU's and implemented as a single module, which is preferable compared to implementing the electronics a parts of each module they control (injection, ignition and emission systems), since the supplier would have to be involved directly in the development and production of each of these modules.

2.5 After sales

During a products life cycle after it has been sold, a number of factors may also be important to consider when defining modules. For service and maintenance purposes, it may be beneficial to simply replace a defective module rather than repairing it while installed in the product. For example an aircraft engine may be replaced with a spare engine, while the original engine is being overhauled. By doing this the airline can still fly the aircraft while the engine is in the workshop, thus reducing the costs of keeping the aircraft on the ground.

Modules may also be defined to allow easy upgrading of a product. Computers are good examples of products which have a modularity that provides easy upgrading of e.g. memory or storage capacity.

The extent, to which a product can be recycled, depends to a large degree on how easy it is to disassemble and separate material into fractions. Hence designing modules that support this would increase the recyclability of the product as a whole. For several years, legislation has required auto manufacturers to design for recycling, which has greatly reduced the number of plastic parts. Battery powered home appliances are other examples of modularisation for recycling, where the product is often designed so that the batteries are easy to take out, when the product cannot be used anymore, so that the battery can be safely recycled.

2.6 Modularity trade-offs

When designing a modular product, it will never be possible to optimize the modularization to address all module drivers. Making a modular design will always require trade-offs between different module drivers and the result will always be a compromise between these drivers. The reason why these compromises are always necessary is that some of the module drivers are contradictory. For example may drivers for standardization and drivers for variety be contradictory and in specific cases, contradictions will always be identified. Ericsson and Erixon (Ericsson & Erixon, 1999) have developed a method for prioritizing module drivers and develop a modular architecture which optimizes the architecture to the best trade-off. In some cases certain module drivers are less important or can be completely disregarded. Designing a product, which is only to be produced in one variant, the module driver for accommodating variety can obviously be disregarded. If development and manufacturing is carried out internally in a company, the module driver for vendor capabilities can be disregarded etc. The more module drivers can be disregarded, the more the focus can be emphasised on the remaining module drivers. It is thus desirable to identify how certain module driver can be disregarded by different means. In the following it will be analysed how The Ten Golden Rules of EcoDesign can influence the different module drivers and even make it possible to disregard relevance certain drivers.

3. Analysis and result.

In this section, based on the categories introduced above, it will be evaluated whether and how the introduced The Ten Golden Rules of EcoDesign (Luttropp & Lagerstedt, 2006) will influence the categories of modularity. The analysis will focus on how EcoDesign will emphasize the use of some drivers and be a facilitator towards sustainable product design.

3.1 Product development

The examples of the camera optics and axel/bearing construction as *geometric integration and precision* are often protected as *structural arrangement* as sealed housing etc. to avoid dust and other influence surrounding environment will have on the vulnerable parts (10GR #7-protect).

The *function share* can as implemented by the example in 2.1 with shared power supply or cooling thus reducing the number of modules and thereby also implies *minimized energy* and *reduce weight* (10GR #3-weight and #4-energy).

The *portability of an interface* supports *repair, prearranged, and promoted upgrading* etc. As an example, take computer add-on RAM modules, which are generic and can, due to the portability of their interfaces, easily be upgraded or one can switch RAM for repair (10GR #8-information and #9-mix).

3.2 Localisation of changes in products

Drivers for designing modules as *carryover*, *technology evolution* and *planned product change* all have impact on development cost, because the drivers all keep some part of product *as is* from a development or evolution point of view, which could be a specific module or the rest of products around the specific module. Eliminating development will inevitable has impact at *long life* for the module or the rest of the product, and to be expected impact at *recycling* and *upgrading* etc. (10GR #5-upgrade, #6-long life, #8-information and #9-mix)

3.3 Variety and standardization

All drivers in this category will have the same influence on the 10GR. Using product configuration as a way to make costumer specific variants, done from a small number of modules, will as well as choosing the common unit and standardization to reduce both development and production cost. When applying modular product architecture, most companies' product strategies would develop modules, which are standardized across multiple products (as described in 3.2). Several standardized modules for the manufacturing will serve as foundation for variety for the costumer. The impact will then be on *minimized energy in production, long life, repair, upgrading, recycling, few joining* etc. (10GR #2-house keeping, #5-upgrade, #6-long life, #7-protect, #8-information, #9-mix and #10-structure)

3.4 Production

The driver *similarity in production technology* will have positive impact on *energy* and *resource consumption* (10GR #2), because using more similar processes yields a higher potential for optimizing those processes compared to using many different processes

Modules based on the driver of *separate tests*, will have no impact on the 10GR. It could be expected that more energy and resources are used, but often the driver is used, when errors in the final test (or missing test) of the product have fatal results for the products use. An example could be a power supply for a satellite, if not tested prior to launch it would be fatal for the satellite operation in space if the power supply failed, in this example one could argue for even more use of energy and resources not using the driver.

Table 4: Module drivers' impact on The Ten Golden Rules of EcoDesign.

Categories	Module Drivers \ Ten Golden Rules	Pre use			Use				After use		
		1) Toxic	2) House keeping	3) Weight	4) Energy	5) Upgrade	6) Long Life	7) Protect	8) Information	9) Mix	10) Structure
Product development	Geometric integration and precis.										
	Function sharing										
	Portability of interfaces										
Localization of change	Carryover										
	Technology evolution										
	Planned product changes										
	Localization of change										
Variety and standardization	Accommodating variety										
	Enabling standardization										
	Common unit										
	Different specification										
	Styling										
Production	Similarity design and prod. techn										
	Process and/or organization										
	Separate testing										
	Supplier available										
	Capabilities of vendors										
After Sales	Service and maintenance										
	Upgrading										
	Recycling										

Vendor Capabilities can have significant influence on structural features, energy used in production, life time, prearranged upgrade, promoted upgrade, recycling, repair etc. because they often have specialized knowledge. Take an azimuth propeller for a large leisure cruiser. The vendor/sub-supplier has knowledge about an effective propulsion, using less energy and less resources, compared to 1 or more huge marine engines and football field long propulsion shafts. Leaving the shipyard in position of designing structural better cruisers expected with lower use of resources, reduction of weight etc. (10GR #2-housekeeping, #3-weight, #4-energy, #6-long life, #7-protect, #8-information, #9-mix, "10-structure).

3.5 After sales

Drivers for modules in this category are all labelled with the "sustainability stamp" and supports more or less *structural features, energy used in production, life time, prearranged upgrade, promoted upgrade, recycling, repair etc.* (10GR #2-house keeping, #3-weight, #5-upgrade, #6-long life, #7-protect, #8-information, #9-mix)

3.6 Results

Presentation of the result as an overview is done in table 4. For overview, green for appliance and/or positive impact/influence of the module driver to The Ten Golden Rules have been used. The grey indicates none impact.

The result presented in table 4 from the sustainability point of view has relatively significant two rules, which seems not or in less degree to have influence at or by the module drivers. At least those drivers are selected for this research. The result reveals that the category "product development" and two drivers within the "production" have little influence on 10GR.

4. Implications and discussion.

4.1 Implications

Since it will never be possible to establish an architecture, where the product is designed optimally for each individual module driver, product designers must choose which module drivers to focus mostly on and which to focus less on. By doing this, it is the intention to achieve the best trade off or a global optimum rather than sub optimising for certain drivers. On the other hand the same issues arise if solely using The Ten Golden Rules, because designers inevitable will look for the best trade off.

From a Mass Customisation point of view an example could be that a customer looking for a sustainable product would easier be able to customise *"a green product"*, because configurators can assist the customer in making suitable choices. This is possible because options can be presented in accordance with EcoDesign rules incorporated in module specifications.

4.2 Discussion

The results presented in table 4 are based on an analysis with chosen examples for this research. These examples have been chosen as the best representatives. It could be challenged whether the chosen examples are representative and if other examples where presented would give slightly other results. However, it will probably not have any influence on the final conclusion.

5. Conclusion

The research presented in this paper and review of papers and articles has revealed that a design approach using product architecture methods, as drivers for modularity, and design rules for sustainability, in general can work together. Module drivers, at least those considered in this research will in general support the goals for sustainability.

A strategic approach pursuing both Mass Customisation and Sustainability, at least from a product perspective using modularity seems feasible.

It can be concluded that from the EcoDesign point of view modules drivers can have positive effect. Specifically it seems that looking for some of the EcoDesign rules in the *Use* and *After Use* categories benefits from modularity.

The research indicates that some design rules for sustainability will not be supported or influenced by using module drivers. Specific avoiding "Toxic" materials in general will not be on the agenda for module driver.

From a Mass Customisation point of view the customers can be offered more sustainable products to address their needs. Modules could besides traditional configuration information, include "green" information, which could be presented as a part of the configuration process, just like performance information, which would assist customers in choosing the most sustainable products.

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Paper 2

Closed Loop Supply Chains for Sustainable Mass Customization

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Closed Loop Supply Chains for Sustainable Mass Customization

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Abstract. Closed loop supply chains reducing waste, energy consumption and natural resource depletion which all contribute to more sustainable production and products. For mass customization however, the challenges of closed loop supply chains are emphasized by the large variety of inbound end-of-life products from customers which complicates handling and forecasting. This paper analyses these challenges in the specific context mass customization using theoretical considerations and three case studies.

Keywords: mass customization, sustainability, remanufacturing, reuse, recycling

1 Introduction

Mass Customization (MC) popularized by Pine [6] has proven a successful business strategy in various industries and markets and for several different product types. Mass customization is fundamentally different from mass production in several different ways, spanning from product design and production to sales and marketing and fit with customer needs. Sustainability is a concept that is gaining more and more attention, and companies are experiencing a greater demand for sustainable products as well as legislation requiring lower environmental impacts [3]. Several concepts are commonly applied to achieve greater sustainability in product design and manufacturing. Among these is Eco-design, which is a concept that attempts to integrate environmental aspects into the product development process thereby creating products with lower negative environmental impacts and thus more environmentally sustainable products [3]. Generally, what happens to a product at its end of life (EOL) is very important in relation to sustainability. This is the case for two reasons: 1) if a product is disposed by land filling or incineration, the materials in the product may harm the environment. 2) The amount of materials available in the world is finite, and if raw materials are extracted at the same pace in the future as they are today, certain materials will become scarce. If an EOL product is simply disposed by land filling or incineration, the materials used in the product are lost, and thus more new material must be extracted for manufacturing new products. Reusing or recycling a product addresses both the issues regarding land filling or incineration as well as resource consumption, since EOL products are either recycled and the materials are transformed into other products or the products are used in their original form. However, even though reverse logistics may help to safely dispose of EOL products, extending the concept to closed loop supply chains has proven to reduce the environmental impact even more [7]. A closed loop supply chain is a combination of a reverse supply chain and a traditional forward supply chain where the components or materials retrieved from products in the reverse supply chain are used to manufacture products for the forward supply chain, thus closing the materials loop.

Rose [7] performed a quantitative Analysis of the environmental impact from a variety of different consumer electronics for the different recycling loops also referred to as EOL strategies. She found that with no exceptions, the environmental impact of a product would increase each time a larger loop was applied. Based on this, she introduced the hierarchy of EOL strategies illustrated in figure 1 [7] and concluded that a product should be designed to apply EOL strategies as high in the hierarchy as possible, corresponding to shorter closed loop supply chains [7].

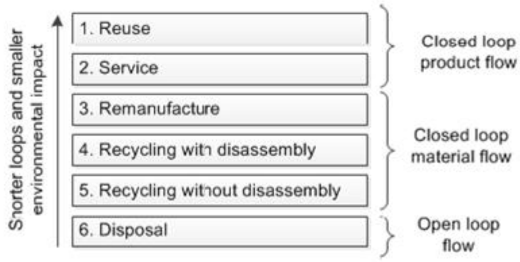

Fig. 1. Hierarchy of product EOL strategies [7]

Apart from the environmental perspective, applying short closed loop supply chains are also usually favorable from an economic perspective. The reason for this is that materials used in products higher in the EOL hierarchy have more value added than lower in the hierarchy. As examples, product reuse requires no or very little additional value added before the product can be used by a new (second hand) customer, whereas a disposed product represents zero or very little value if it is incinerated for energy production.

2 Research Method

The research objective of this paper is to identify how well mass customized products can become more sustainable by utilizing closed loop supply chains. The research question is: "How can end-of-life strategies with closed loop supply chains be applied to mass customized products?" To answer this question, it is first clarified how well the EOL hierarchy and mass customized products combine. Secondly the concepts of closed loop supply chains with different EOL strategies are analyzed for various mass customized products. Finally the findings from the analysis and the case studies are identified and presented. The analysis is performed as an empiric research based on

Rose's product EOL strategy hierarchy as presented in figure 1. It is analyzed which issues typically arise for mass customized products in end-of-life. This is done for each of the 6 levels in the EOL hierarchy (fig. 1). The concepts of closed loop supply chains are further analyzed in three mass customization cases all with EOL strategies and different levels in the hierarchy. The case studies present and analyze how the EOL strategies have been implemented in consumer electronics, automobile and furniture industry. The findings from the analysis and case studies are presented as a general overview of advantages and disadvantages of mass customized products combined with EOL strategies and a comparison of EOL strategies of the case studies.

3 Closed loop Supply Chain and Mass Customization

Much research has been done in the areas reverse logistics and closed loop supply chains, however, no studies have been identified focusing on these issues related specifically to mass customized products. Mass customized products are distinguished from non-mass customized products, primarily by their vast variety, as each product is uniquely produced for a specific customer. This is expected to bring up new challenges in relation to reusing and recycling products. In the following sections, the challenges specific to mass customized products will be discussed. The analysis will be structured by the levels in the product EOL strategy hierarchy shown in figure 1.

3.1 Reuse

Reuse (1) is the EOL strategy which will use least resources compared to other EOL strategies, simply because following the definition expressed by Rose [7] as "… the second hand trading of a product for use as originally designed", the products involved in a reuse process change owners without any involvement of the original manufacture and other further resources involved. Implementing reuse as an EOL strategy should be easy for standard products but for MC products there are several difficulties which have to be addressed.

One issue related to MC products is that the customized product specifically made for a specific customers requirements, can be difficult to reuse. Difficult to reuse, because the products will not fit the new customers' requirements; as examples, it could be tailor fitted products, as suits, shoes, furniture etc.

Implementing an EOL strategy should on the other hand lead to MC products which should be easy to reuse and even in the reuse process are able to customize further for the second hand owner.

3.2 Service

If a product is to be replaced due to "wear and tear", i.e. the product is somehow worn or defective and thus cannot be reused, which is the preferred EOL strategy according to the hierarchy, the strategy "service" should be considered [7]. In this strategy, the life of a product is extended by repairing or servicing the product thus pushing the time where a new product will have to be manufactured to fulfill a user's needs. There is no apparent and strong relation between this strategy and mass customization, however the variety of parts included in the product may cause some issues if spare parts are necessary. This would be the case if the parts, which are to be replaced to repair the product, are custom fabricated, as opposed to a customized product assembled from standard components. If a custom fabricated component is required for repairing or servicing the product, this would likely be more expensive than repairing a product using standard components, since the spare part would need to be manufactured specifically for that product which would likely introduce higher logistical costs as well as a problem regarding the identification of specifications for manufacturing that specific part.

An example of mass customized products which have a modular architecture that supports upgrading is personal computers. If a user finds that a computer is lacking certain functionality or performance, in many cases this will be possible to address by adding or replacing modules in the computer such as CPU, processor or other expansion cards. This is obviously more appropriate from an environmental perspective since a new computer will not have to be produced to fulfill the user's new needs.

3.3 Remanufacture

The EOL strategy remanufacturing implies according to Rose [7] that EOL products are returned from the customer to a remanufacturing plant where they are disassembled; the parts are reconditioned and used in the manufacturing of new products using newly manufactured parts as well. In contrast to the service EOL strategy, the product is here completely disassembled and components are collected and kept in stock until needed. By choosing the remanufacturing strategy, the material and energy used for originally manufacturing the products is not lost which apart from reducing negative environmental impact can be economically beneficial as well [9].

The degree to which an MC product is suitable for remanufacturing will be very dependent on how the product architecture is defined. One way to mitigate the challenges derived from component variety described above by means of product architecture would be to enable remanufacturing of the components common to all products in a product family, commonly referred to as the product platform, which is commonly used in MC products [1], whereas the modules providing customization could be recycled for materials. This however would require the components in the platform to be sufficiently durable for multiple life cycles.

3.4 Recycling with Disassembly

When applying the recycling with disassembly EOL strategy, EOL products are taken to recycling facilities where they are disassembled and recycled. In contrast to recycling without disassembly, this strategy implies that the value and energy accumulated in the products is to some extent retained. Recycling with disassembly also allows removing components or substances which would otherwise contaminate the recyclable materials, as well as valuable components can be removed and reused or remanufactured [7].

When considering recycling with disassembly in relation to MC products, several different factors influence the possibilities for recycling. As the products need to be disassembled, which is usually a manual process, the disassembly process is likely to account for much of the total costs associated with recycling. As MC products will often have varying product structures compared to non MC products, the disassembly process will also vary more than for non MC products. As a consequence, it will be more difficult to optimize the disassembly process as well as applying automation.

3.5 Recycling without disassembly and disposal

Recycling without disassembly is the EOL strategy with the longest materials loop and thus the least desirable of the closed loop supply chain strategies, however still preferable over disposal. Recycling without disassembly is usually performed by shredding; by doing this the shredded products can be sorted into material fractions which can be recycled. Since all products are treated alike when recycled without disassembly, no specific challenges regarding MC products are identified for this EOL strategy. The EOL strategy disposal is the least desirable in the hierarchy, since the value and energy accumulated in the products is not recovered. As for the recycle without disassembly strategy, all products are treated alike when disposed, and no specific challenges regarding MC products are identified for this EOL strategy.

4 Case Analyses

To address how different types of companies have been using reverse logistics in practice, a number of case studies have been identified in literature.

Dell Inc. sells and produces personal computers which are all customized according to the customer specific configuration. Dell has implemented a closed loop supply chain to make use of EOL computers which are traded in by Dell's customers. This case is thoroughly described by Kumar & Craig [5]. When comparing the paths of EOL computers at Dell to the classification of EOL strategies shown in figure 1, Dell makes use of several of these strategies:

- Reuse: EOL computers which do not require any parts changed are reinstalled with an operating system and resold, physically unchanged.
- Service or Remanufacture: computers which require replacement of components are changed physically and are, depending on how many components are changed, either serviced or remanufactured.
- Recycle with disassembly: computers which are not reused, serviced or remanufactured are disassembled and shipped to appropriate recycling facilities.

This multilevel approach to handling EOL computers allows Dell to utilize the shortest closed loop supply chain as possible. What enables this is that the modularity of Dell computers allows components to be easily replaced and allows reuse of components from EOL computers. Furthermore, Dell's volume makes it profitable to run remanufacturing facilities.

Numerous car manufacturers are mass customizing their cars. This is enabled by a modular product platform which allows customization by assembling the car from a common platform and a number of different modules creating the variety. Contrary to the Dell case, car manufacturers do not take back whole cars for remanufacturing, which can be due to a number of reasons. Cars usually have a much longer life than personal computers and are thus regularly serviced for extending their life. Relating the automobile industry to the classification of EOL strategies in figure 1, it shows that the car industry also utilizes multiple levels.

- Service: When a used car is traded in by a dealership, it is serviced and resold, typically in an unchanged configuration; however, the car manufacturer is not involved in this.
- Remanufacturing: Worn components are traded in for a discount on a remanufactured component and remanufactured to as new condition by specialized companies
- Recycling with disassembly: EOL vehicles are returned to third party car recycling facilities and disassembled for spare parts and material recycling.

The automobile industry is similar to the Dell case since mass customized products are resold in a fixed configuration which cannot be reconfigured.

Ahrend is a Dutch manufacturer of office furniture, which has done a significant effort on reducing the negative environmental impact from production and product life cycles. Ahrend produces office chairs and desks for the professional market and their furniture are individually customized and can thus be considered mass customized products. Ahrend has as one of the means to control supply of EOL products, introduced a residual value on repurchase program for its customers allowing them to return their product to Ahrend after ended use and receive a partial refund. After receiving the used products Ahrend is to refurbish certain components and renew others and sell new products which contain refurbished as well as new components. These new products are again customized. Comparing the Ahrend case to the EOL hierarchy of figure 1 shows that Ahrend contrary to the two other cases makes use of remanufacturing used products to create new mass customized products by reusing on module level.

5 Findings

In figure 2, an overview of the different EOL strategies and their implications for MC products is presented. For the upper 4 levels a number of challenges exist which are specific to MC products, however a number of characteristics of MC products also provide benefits for the different closed loop supply chain EOL strategies compared to non MC products. Finally, no differences were found for the lower two EOL strategies between MC and non MC products.

Figure 3 shows a comparison of EOL strategies chosen in the three different cases presented in this paper as well as the EOL options for a generic MC product. For a generic MC product, i.e. any MC product, for which the manufacturer has not actively chosen an EOL strategy, the options for the customer when disposing the product will be either to sell it as second hand, given the second hand purchaser can accept the product configuration or bring it to recycling facilities or disposal. What can also be concluded from the comparison is that in only the Ahrend case, the products are remanufactured and offered as individually mass customized products again, whereas the other two cases offer used products in an as-is configuration. It is furthermore common to use mixed EOL strategies, since the difference in wear and obsolescence makes different EOL strategies suitable for different products in the supply of used products.

	Advantages	Disadvantages
Reuse	Reconfigurability allows customization to new user	Poor fit to diverse customer demands
Service	Modularity enables replacement of defective modules	Product variety increases variety of spare parts
Remanufacturing	Modular products enable component replacement Product platform architecture enables remanufacturing of modules common to one product family	Product variety in EOL product supply complicates demand planning Custom manufactured components are unsuitable for remanufacturing
Recycle with disassembly	Easier disassembly due to modular product architecture	Difficult to optimize or automate disassembly process due to product structure variety
Recycle without disassembly	None	None
Disposal	None	None

Fig. 2. Overview of product EOL strategies and implications for mass customization products compared to mass produced products

As mentioned above, many MC products can be reused in an as-is configuration. While this would likely be beneficial in terms of environmental impact, the business potential is negligible unless the manufacturer is involved in the second hand trading of the product as in the Dell case.

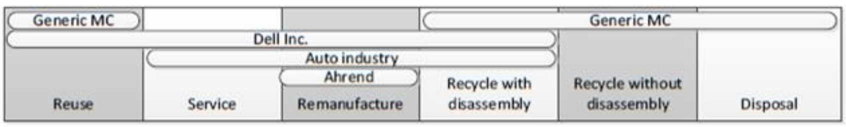

Fig. 3. Comparison of EOL strategies for case products

Finally the case comparison revealed that there are differences in whether the manufacturer manages the closed loop supply chains or a specialized third party company is involved. General for all cases is that the product families apply modular product architectures, which is not surprising since modular architecture enables mass customization and remanufacturing [2], [4].

6 Conclusion

From the analysis of EOL strategies and cases it can be concluded that it is indeed possible to utilize closed loop supply chains in mass customization settings. However, utilizing closed loop supply chains requires certain aspects to be considered regarding product design as well as manufacturing and supply chain design.

Utilizing closed loop supply chains has a great potential in achieving a higher degree of product sustainability, since this will reduce the amount of waste produced as well as reducing the demand for raw material production and energy consumption. Although only a minor part of mass customizers are utilizing closed loop supply chains, the case studies have shown that it can be an attractive business proposition to e.g. remanufacture products and resell them.

However, to provide the customer with the highest value, and thereby charge a price premium, the remanufactured product should be re-customized to specific customer requirements as done in the case study of Ahrend instead of reselling products as second hand in as-is configurations. This however presents a number of logistical challenges as well as challenges in developing the solution space for configuring remanufactured products. Furthermore, this research addresses only mass customization of physical products. Mass customization of services and software is also relevant but will require entirely different considerations regarding sustainable supply chains.

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Paper 3

Sustainability Evaluation of Mass Customization

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Sustainability Evaluation of Mass Customization

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Abstract. This paper addresses the issue whether the concepts mass customization and sustainability are fundamentally compatible by asking the question: can a mass customized product be sustainable? Some factors indicate that mass customized products are less sustainable than standardized products; however other factors suggest the opposite. This paper explores these factors during three life cycle phases for a product: Production, Use and End of Life. It is concluded that there is not an unambiguous causal relationship between mass customization and sustainability; however several factors unique to mass customized products are essential to consider during product development.

Keywords: mass customization, sustainability, remanufacturing

1 Introduction

Mass customization (MC), popularized by Pine et al. have proven a successful business strategy in various industries markets and for several different product types [10]. Mass customization is different from mass production in several different ways, including product design and production to sales and marketing and fit with customer needs.

Sustainable development is defined by the Brundtland Commission as "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [4]. Sustainable development includes three dimensions: the environmental, economic and social dimensions [4]. However, in this study it is chosen to focus on the environmental dimension of sustainability.

Sustainability is a concept that is gaining more and more attention, and companies are experiencing a greater demand for sustainable products. Several concepts are applied to achieve greater sustainability in product design and manufacturing. Among these is Eco-design, which is a concept that attempts to integrate environmental aspects into the product development process thereby creating products with lower negative environmental impacts and thus more environmentally sustainable products. Since mass customizing companies, just like every other company, will have to consider sustainability, it is relevant to consider how mass customized products are different from mass produced products in a sustainability perspective.

2 Research Method

The research objective of this paper is to identify mechanisms in mass customization, which can yield mass customized products more sustainable or less sustainable compared to traditionally mass produced products. The research question is: "How can the elements of mass customization influence the environmental sustainability of a product?" To answer this question, it must first be clarified which elements of mass customization are addressed in this context. Secondly the concept of environmental sustainability must be clarified. Finally the interrelations between these two concepts are identified and analyzed. To structure this analysis, the interrelations are grouped according to the product life cycle. Rose [11] presented a generic product lifecycle, which is illustrated in figure 1.

Fig. 1. Generic representation of a product life cycle (Rose, 2000)

The first stage, materials extraction and processing, is not expected to have strong relations to whether a product is mass produced or mass customized and this stage is thus disregarded in this paper. Furthermore, the manufacturing and assembly stages are joined into one stage. The analysis is thus divided into the following phases of a product lifecycle: 1) Production, 2) Use and 3) End of Life. For each of these phases, mass customization and mass production products are compared

Within the first two areas, production and use, the analyses are structured on basis of concepts which are characteristic for mass customization production and products. More specifically, the factors described by Berman [2] and Maccarthy [8] have been reviewed and those which were found to have relevance for this study have been included: 1) Product Modularity, 2) Process Variety, 3) Distribution Channels, 4) Improved fit with customer needs & 5) Product functionality customization.

Furthermore, concepts which have their origin in sustainability research have been identified through literature studies. The concept of reducing energy consumption, which is essential in eco design as well as life cycle thinking [6], is included as well. In the End of life stage, a number of end of life strategies identified by [11] are included in the elements which are analyzed: 1) Energy efficiency, 2) Reuse, 3) Service, 4) Remanufacturing, 5) Recycling and disposal. In the following, the elements presented above and their relations will be analyzed.

3 Analysis

3.1 Production

Modularity is usually considered a key enabler for efficient mass customization [10] and thus most producers of mass customized durables apply modular product architectures. Ulrich et al. describe modular product architecture as the opposite of an integral architecture [12]. The advantages of an integral architecture are usually that the performance of a product can be improved compared to a modular product. In this context, the performance could among other things be properties like size and weight. It is generally acknowledged to be good practice in EcoDesign to minimize usage of material resources in manufacturing [7]. Since mass customized products are usually modular and following the arguments from Ulrich et al. [12], it could be expected that more material resources are necessary to produce those compared to mass produced products, since modular products cannot be optimized with regards to weight and thereby material usage as mass produced products. This is assuming that the mass produced product is optimized for minimum material resource usage by applying integral product architecture. Hence, mass customized products may have a greater environmental impact during production due to a higher material usage.

In relation to process variety, mass customization requires much higher process flexibility compared to mass production due to the higher product variety and subsequently process variety [2]. The fact that many more different manufacturing processes are necessary to product customized products compared to standard products makes it more difficult to optimize the processes with respect to energy and material consumption. Hence the fact that the process variety is higher in mass customization may imply a greater environmental impact than mass production.

An element of mass customization which differentiates it significantly from mass production is the distribution channels. In mass production, a finished product may be distributed through several tiers of distributors before being purchased and taken to the final customer. In contrast to this, mass customized products are produced for one specific customer and are thus possible to distribute directly from producer to end customer. This could serve as an argument for mass customization to have both a higher and lower environmental impact compared to mass production in relation to distribution.

The argument for a higher environmental impact would be that each product is distributed individually from manufacturer to customer, which would require more packaging and presumably more energy, since each product would take more space compared to a larger number of similar standard products, which could be packaged and distributed together. The argument for a lower environmental impact would be that the product does not travel through multiple tiers of suppliers and thus is expected to have a shorter route from producer to consumer which could again be expected to consume less energy and fewer emissions.

Finally, to be able to deliver a mass customized product to the customer within an acceptable time, it can be beneficial to produce the product closer to the customer than for mass produced products. The reason for this is that mass produced products can be produced geographically far away from the customer, but given they are standard products, they can be kept in stock close to the end customer. This is of course not possible for customized products and this distribution strategy is thus not feasible for mass customization. This is a reason why mass customized products are more likely to be produced close to the end customer than mass produced products and as a consequence the product has to travel a shorter distance from producer to end customer yielding lower energy consumption in the distribution.

3.2 Use

When a customer chooses to purchase a mass customized product, this will most likely provide an improved fit between the product's properties and the customer's needs [2], compared to purchasing a standard product.

For certain groups of mass produced products, the purchase price is so low that consumers do not hesitate to dispose a nearly unused product if it does not meet the customer's needs and purchase a replacement, assuming that it will better fit the needs. However, this will likely produce extra negative environmental impacts, since the product reaches its end-of-life before it has worn out. One example of this from the apparel industry is presented by Hethorn et al. [5]. Much apparel is so inexpensive that many customers purchase clothing which may not fit. Clothes that do not fit are unlikely to be worn by the customer, and the resources for producing those clothes are thus wasted, and the resources for producing clothes for that customer, from an overall perspective, could be reduced.

Creating products that have a better fit with the customers' needs could thus reduce the waste that is produced by manufacturing products that are never used. Mass customization presents an opportunity to do just that, since the better fit that customers achieve by choosing a mass customized product would logically reduce the probability that the product is not used and that the resources used for manufacturing it are thus wasted. This goes not only for apparel but for other product types as well which have a cost low enough for customers not to hesitate disposing even an unused product if it does not fit their needs. Hence the mechanism that mass customization provides a better fit introduces an opportunity that mass customization products could reduce the type of waste presented above.

In relation to production it was described above that integral product architecture would usually yield a greater potential for optimizing the product with respect to performance compared to modular product architecture. One other aspect where this is relevant in relation to environmental impact is the energy efficiency, which obviously is only relevant for those durables that consume either electricity or other energy sources. Given that most mass customized products are modular; this is another mechanism that could render mass customized products less environmentally sustainable than mass produced products which have the potential of being more optimized for energy consumption than mass customized products.

There is however an argument which could counter this mechanism. Applying modular product architecture, most companies would attempt to establish modules which are standardized across multiple products. This would then imply that the company due to the larger volume could, invest larger sums in optimizing that particular module thus potentially achieving greater energy efficiency than a mass produced product, given that module is was is produced in larger numbers than individual mass produced variants.

3.3 End of Life

Rose [11] presented the hierarchy of end-of-life (EOL) strategies which is illustrated in figure 2. Generally, in order to minimize the environmental impact at product end of life, strategies higher in the hierarchy should be chosen. Strategies 1-5 are so called closed loop strategies [1], and are preferable to open loop strategies (6), since they make use of the value and resources already added to the raw materials [11]. End-of-life in this context is defined as the point in time where the original user does no longer wish to use the product for whatever reason.

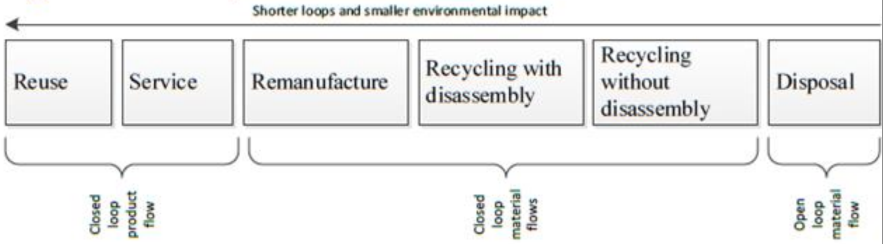

Fig. 2. Hierarchy of End-of-life strategies from [11]

The EOL strategy reuse implies that the product at EOL is obtained and used by a new user without modifying or refurbishing the product. This strategy implies no consumption of resources and makes it unnecessary to manufacture a new product thus reducing the resources needed to fulfill the customers' needs. Considering this strategy in relation to mass customization presents a critical issue: Since mass customized products are tailored to an individual customer's requirements, it is unlikely that the product's properties will fit an entirely different customer's requirements, since those requirements would need to be uniform. For example it is unlikely that for example a T-shirt customized with some personal information, e.g. a photo or a name would be worn by someone else than the original buyer. Hence we can conclude that there is potential complication in designing a mass customized product that can be "reused" in their original form. There are however mechanisms which can counter this issue. If mass customization of a product is achieved by designing a self-customizing product as presented by Alhstrom et al. [1], a new user of the product would simply re-configure or re-personalize the product to meet the new requirements. Hence, it cannot be unambiguously concluded that mass customized products cannot be re-used and therefore be optimal in relation to their EOL environmental impact.

If a product is to be replaced due to "wear and tear", i.e. the product is somehow worn or defective and thus cannot be reused, which is the preferred EOL strategy according to the hierarchy, the strategy "service" should be considered [11]. In this strategy, the life of a product is extended by repairing or servicing the product thus pushing the time where a new product will have to be manufactured to fulfill a user's needs. There is no apparent and strong relation between this strategy and mass customization, however the variety of parts included in the product may cause some issues if spare parts are necessary. This would be the case if the parts, which are to be replaced to repair the product, are custom fabricated, as opposed to a customized product assembled from standard components. If a custom fabricated component is required for repairing or servicing the product, this would likely be more expensive than repairing a product using standard components, since the spare part would need to be manufactured specifically for that product which would likely introduce higher logistical costs as well as a problem regarding the identification of specifications for manufacturing that specific part. Many mass customization products are designed using modular product architecture to be able to efficiently manufacture custom products. The nature of a modular product would likely enable upgrading the product, given that upgrading possibilities has been considered when defining the product architecture. Comparing this to a standard product, which may not have a modular architecture which is prepared for replacing or adding modules, the modular mass customization product would be possible to upgrade compared to a standard product, where modules with variety are not readily available.

The third level of the hierarchy, remanufacturing implies, as well as the two recycling levels, the closed loop material flows in the hierarchy [11]. Remanufacturing is defined by Nasr et al. [9] as: The process of disassembling, cleaning, inspecting, repairing, replacing, and reassembling the components of a part or product in order to return it to "as-new" condition. As described above, many mass customized products will have modular product architecture. Modular products can generally be expected to be more appropriate for disassembling compared to integral products [3]. It should be noted in this context, that this relationship is based on the product architecture (modularity) and not the customization of the product. Hence this relationship can also be applicable for standard products given they are based on a modular architecture.

Many mass customized products are configured using configurator software and a specific configuration can be traced to a specific customer. This implies that the manufacturer is likely to have knowledge of exactly which customers do have a product that can be taken back for remanufacturing thus enabling companies to provide incentives to the customer for returning and EOL product. Using remanufacturing as an EOL strategy for mass customized products, products can be disassembled into modules which are stored and reassembled to new products configured to match a new customer's requirements. As for the service EOL strategy, custom fabricated components complicate this strategy since it may not be possible to remanufacture these and hence must be recycled, which is less desirable. It can thus be concluded that remanufacturing is likely to be a good EOL strategy given the mass customized product is not self-reconfiguring and does not contain custom fabricated components.

In levels 4 and 5, EOL strategies are less desirable than the strategies where the entire product is reused, however preferable to disposal. Mass customized products are often modular and thus easier to disassemble than standard products which are more likely to be non-modular. This is of course relevant for the "Recycling with disassembly" EOL strategy. Furthermore, modular product architecture will enable concentrating certain material fractions in certain modules which will likely increase the recyclability.

4 Analysis of results and implications

The results of the analyses performed in section 3 are summarized in figure 3. As it can be seen from this figure there are several relations between the elements of mass customization and environmental sustainability that indicate that mass customization does have an effect on the sustainability of a product. In figure 3, the boxes above the dashed line represent concepts which are typically addressed by researchers and practitioners within mass customization, whereas the boxes below the line repre-

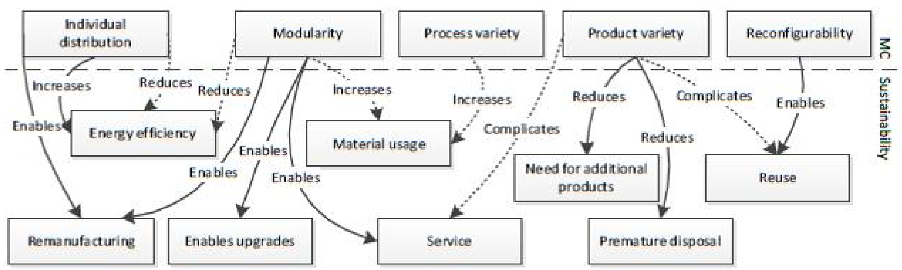

Fig. 3. The relations between mass customization and sustainability

sent the elements of sustainability that were found to have a relation to mass customization.

The dotted arrows from the mass customization concepts to the sustainability concepts represent the identified relationships where mass customization potentially has a negative influence on sustainability compared to mass production. The solid lines are opposite and represent relationships where mass customization can be expected to be more sustainable than mass production. Eight positive relationships and six negative relationships were identified; however these numbers cannot be used for concluding that mass customization is more sustainable than mass production, since these relations are not unambiguously quantifiable, since they can only be quantified for specific products, as different products will have different environmental impacts. What is also interesting is that not several single elements of mass customization potentially have both negative and positive effects on sustainability compared to mass production. One example of this is the individual distribution, which can have both negative and positive impact on the energy efficiency during distribution.

This finally implies that the assessment of whether mass customized products are more or less sustainable than similar mass produced products will depend entirely on individual studies. Consider two completely different products; an automobile and a piece of clothing. The environmental impact profiles of these two products are completely different. The automobile will consume much more energy throughout the use phase of its lifecycle than consumed during product phase, whereas a piece of clothing will consume no energy during its lifecycle. Furthermore, an automobile is much more likely to be serviced to extend its life cycle and to be reused when its original purchaser disposes of it. Hence, the difference between mass customized and mass produced products will vary greatly between these two groups of products.

From the results of the analysis in section 3 there is no indication that mass customization should have the potential to be less sustainable than mass production. The results presented can thus be used as guidelines for how to address sustainability issues in mass customization by pointing out areas where mass customization is different from other business strategies, thereby assisting in tailoring strategies for becoming more sustainable.

5 Conclusion

It can be concluded that there are indeed many elements of mass customization which can influence the environmental sustainability of a product if it is compared to a similar mass produced product. However, since there are both factors which contribute more sustainable and less sustainable products, a universal conclusion cannot be drawn for all mass customized products. It can thus be concluded that mass customization it not either sustainable or unsustainable, but has indeed the potential to contribute to sustainability.

The work presented in this paper is a qualitative study to explore the links between mass customization and sustainability. Further research could analyze these relations using a quantitative approach for specific product types to analyze the relations in specific cases.

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Paper 4

Categorizing Variables Used for Product Configuration

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CATAGORIZING VARIABLES USED FOR PRODUCT CONFIGURATION.

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Abstract: *The number of combinations which can be calculated for configured products is often an enormous number. The number, even if it could be handled, still does not indicate how much customer variety or manufacturing complexity it causes.*
Based on an empiric case study, this research indicates that it is necessary to categorize the variables for mechatronic product to identify customer variety and manufacturing complexity. It is indicated that customer variety and manufacturing complexity cannot be depicted from the type of variables alone, hence more research is needed. Earlier research has indicated that designing mechatronic products for product configuration and mass customization could be done from a structure / function design view, which is discussed in this paper.

Key Words: ***Mass Customization and Personalization, Mechatronic Products, Product Configuration***

1. INTRODUCTION

The advantages of using Customization and aiming for use of Product Configuration (PC) when designing mechatronic products has been revealed in previous research [1]. Since customers have individual demands, manufacturers have to decide to what level these demands must be fulfilled. Many suppliers have learned that many product variants may increase the cost of manufacturing dramatically and non-profitably.

Mass Customization (MC) introduced by Davis [2] and followed by Pine [3][4], is often seen as a solution to this problem and, since then, MC has called for a change of paradigm in manufacturing. Several companies have recognized that MC is needed and much effort has been put into identifying, which success factors are critical for an MC implementation and how different types of companies have used it beneficially [5][6][7][8].

The best way to implement MC most appropriately varies and, for obvious reasons, there are different strategies between different companies, markets and products. Newer research underlines that MC is a strategic non-reversible development and suggests that the change process is considered as a strategic mechanism [9]. Because there is not one single generic strategy, it is important to look at the issue from different viewpoints.

The fact that products must be easily customizable in order to achieve MC has been described comprehensively in the literature and, more generally, [5]and [4] have discussed the issues related to readiness of the value chain.

One area of interest is the variety PC and MC creates. Obviously optimized variety is in the interest on the customer side and on the other side a minimized manufacturing complexity is of interest in the production [10]. In applications it would be addressed as high variety for the customer and less variety for the production. Looking specifically at mechatronic products; an optimization with less variety in the structural level and higher variety in functional level could have some interest [1]. An optimization of variety between the structural level and functional level would present more variety for the customer and presumable less manufacturing complexity in the production.

Since designing and redesigning products would aim for less manufacturing complexity in the production and higher variety for the customer, methods to identify manufacturing complexity and variety could have some degree of interest. Both could be simplified to do a measurement of the variety or the numbers of variants, a combination of the product's modules and variables would create. Parameters like less or higher numbers of variety could then be the goals aiming for redesign or new design.

How can it be determined if a design or re-design is less complex to produce and have higher variety for the customer? In which way can a (simple) calculation give an indication of manufacturing complexity and customer variety? To answer these questions a case study [11], has been done as an empiric survey and has included ten products, marketed and sold with the use of product configurators.

The result is – not surprisingly - that numbers of variants or the variety grows to numbers we are unable to comprehend. The variety calculated for relatively simple products can easily reach number at 10^{12}, 10^{15} or higher. Furthermore the results show that calculation of combinations will not reveal any kind of potential manufacturing complexity a single variable can cause in the production line.

It is concluded that further survey has to be done to categorize the variables; and it is likely that the classification can be used as a foundation to form a simpler way to calculate the variety and manufacturing complexity.

2. METHODS

As stated, an empiric survey, covering ten products all sold by use of a product configurator, has been done. The result of the survey has established facts about the number of variables, what type of variables, and the number of constraints involved in the product configuration process. Based on the result a number of combination, a configured product can produce, is calculated for each of the involved products. Results of the empiric survey are used as base for the discussion and conclusion.

For the empiric survey ten products was selected with the restriction that the product configurator should be available on-line. Diversity in the list of ten was established by randomly doing a gross listing approx. 25 products found by choosing among the list of companies using product configurators found at Configurator Database [12]. The list of ten, to be used for the survey, was selected as a pre-survey done by visiting the homepage of each company from the gross list. The degree of use of product configuration was subjectively assessed and because several of the product configurators have entries to more than one product model, one model has been selected for the survey. The final list of ten was then subjectively made from this list.

The survey was performed as a registration of 1) the variables representing the product family, 2) selection of type of variables 3) constraints found. The type of variables is divided into 3 classes (A, B and C),: variables, type A, with a fixed set of possible identifiers e.g. 'red', 'blue', and 'green' or, e.g. 'round' and 'square', variables type B, with discrete integer interval of values, e.g. n = [4,,18], and variables, type C, with continuous interval of values, e.g. x = [4;18].

The results of the survey are in a table presented as a summary of ten individual tables.

Through analysis, of the data collected, it will be assessed if they can reveal the information which is necessary for optimizing variety for the customer and reduce manufacturing complexity in production.

3. RESULTS

Input data for the survey is presented in the following table (Table 1). The input data has been achieved by use of a random and subjective selection process. All input data has been retracted from the Configurator Database and used as input during the period of survey from 3rd of March to 6th of March 2010

The survey has resulted in individual tables for each of the product family involved in the survey and these tables has been summarized in one table (table 2).

Based on the result from the survey a combinatory calculation of the variety has been done (table 3).

Table 2 *Datasets for the survey.*

Company	Homepage	Product family
Konrad Krauss	kraus.atbit1.de	Dino Dual
DELL	www1.euro.dell.com	Latitude E5400
SparVinduer	sparvinduer.dk	dannebrogsvinduer
Pool Power Shop	poolpowershop.de	Oval
Mars Inc.	mymms.com	Na
Akkuline	akkukonfigurator.de	Na
FootJoy	footjoy.com/myjoys	FJ ICON Trad.
Tailor Store	tailorstore.se	Skjortor
BMW	bmw.de	X6
Hanse Yacht	hanseyachts.com	545

A number of possible combinations have been calculated and the result is under influence of the constraints involved. How much or how little influence the constraints have on the combinatory calculation cannot be resolved directly from the data collected in the survey, but a subjective assessment of the variables with constraint relationship has been used to remove non existing combinatory variants.

Table 3 *Summery of the survey.*

Company	# Variables	Type A	Type B	Type C	# Constraints
Kraus	7	5	1	1	1
DELL	26	26	0	0	5
Sparvinduer	10	7	1	2	2
Pool Power	7	7	0	0	5
Mars	7	3	2	2	4
AkkuLine	11	8	2	1	2
FootJoy	16	12	4	0	9
Tailor Store	41	27	1	13	18
BMW	61	60	0	1	31
Hanse Yachts	28	28	0	0	13

Furthermore type C variables, with continuous interval, has been grouped into discrete intervals (inspired by Shaw [13]) to avoid the result of combinatory calculation to be infinitive.

Table 1 *Calculation of combinations based on the variables*

Company	Combinations
Kraus	$2,1\ 10^{7}$
DELL	$4,0\ 10^{12}$
Sparvinduer	$3,1\ 10^{13}$
Pool Power	$1,1\ 10^{4}$
Mars	$1,1\ 10^{22}$
AkkuLine	$1,8\ 10^{8}$
FootJoy	$1,4\ 10^{31}$
Tailor Store	$3,7\ 10^{57}$
BMW	$1,3\ 10^{28}$
Hanse Yachts	$3,4\ 10^{17}$

4. ANALYSIS

Based on the results presented in Table 2, it is not possible to establish exact knowledge about the variety or manufacturing complexity. None of the data collected individually or combined reveals any specific expression of the variety or manufacturing complexity.

By analyzing the number of variables involved in a product configuration (Table 2) it is relatively evident that 3 of the ten candidates (Krauss, Pool and Mars) have the lowest number of variables and as an opposite a different candidate (BMW) has the highest number of variables involved. But none of these numbers can be used as an assessment of how optimized the offered variety to the customer is. Looking at the variety they can be configured to, shown in Table 3, they have great differences, but it can (only) be established that we have high numbers of variety no matter which of the products we choose among.

To review the manufacturing complexity the results gives no exact information, and going closer to each variable involved, neither of the data collected gives any further information about the manufacturing complexity. Reviewing individual variables by using the classification set prior to the survey, neither can reveal the manufacturing complexity involved.

5. DISCUSSIONS

Based on the result and analysis it can be argued that using a classification of variables as in the empiric survey presented seems not to clarify how much customer variety or how much manufacturing complexity these variables cause.

Analyzing the types A versus B/C variables, it seems that doing the combinatory calculation for possible variants the results have a distortion coming of the nature of B/C types. Type B/C variables will not necessary cause more manufacturing complexity if the interval is a few variants or many, e.g. 5 variants compared to 100.000.000.000 variants, by using parametric design would not necessarily cause a higher degree of manufacturing complexity. On the other hand an outcome change from 2 variants to 4 variants for type A variables will probably cause a double manufacturing complexity.

Earlier research has indicated that it would ease the design process of mechatronic products for PC and MC using a framework of structure and functions [1]. Reviewing the literature in the design domain [14] [15] [16] [17], the use of function – behavior – structure framework has revealed a possible path to categorize the variables. Relation between the function / structure and customer variety and manufacturing complexity is discussed in the following paragraphs.

It is argued that manufacturing complexity is related to the structure of the device [17][14]. Using such a view will identify relationships of components because the representation is based on the physical organization of components, which could represent the manufacturing complexity as well. The structure framework of physical components could be expressed as a set of variables. For example a plain table consists of 6 components four legs, a frame, and a tabletop. This could be set as 3 variables all a part of the manufacturing complexity, take the variable *legs* and make them variable in two materials as wood and metal. Make *wood* available in oak and birch, and metal available in chrome and 2 colors. Wood and metal would be twice manufacturing complexity. Manufacturing of oak or birch will not apply further complexity, but legs in chrome or in 2 colors would apply further manufacturing complexity.

It could be argued that the use of functional structuring [17][14] could reveal the customer variety, because in a functional structuring representation a devices set of functions could be expressed as a set of variables. In functional structuring it is possible to decompose the device's function into components' functions. For example the table is now with adjustable height of legs. The function *height of table* could be design as several fixed lengths of sets of legs, or manually adjustable legs, or motorized adjustable legs. Each type is representing the same function *height of table*, which is comparable with the customer variety.

6 CONCLUSIONS

Clarifying a way to express the customer variety and the manufacturing complexity of customizing products was the initial scientific goal. An empiric survey was the foundation for datasets to be analyzed and discussed in this paper. The survey based on ten product models was used as reference to establish the knowledge about how to express variety and manufacturing complexity.

It has been revealed that it is not possible from those data collected in this survey, that customer variety can be expressed using knowledge about the variables variants and the type of variable. It is possible to calculate a number of possible variants as a simple combinatory calculation, but it has also been clarified that this number in a practical application would be so large that it cannot be processed for any kind of action to take. It is concluded, as well, that the manufacturing complexity cannot be revealed from a list of variables without further information about the variable.

For further research is has been indicated that using a function – behavior – structure framework could reveal how to categorize variables to express manufacturing complexity and customer variety.

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Paper 5

A Framework Study on Assessment of Mass Customization Capabilities

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A FRAMEWORK STUDY ON ASSESSMENT OF MASS CUSTOMIZATION CAPABILITIES

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Abstract: *Reasearch proposed that three fundamental capabilities are evaluated as a company's status of mass customization.*
This paper will introduce a framework for measuring and assessing a company's performance as a mass customizer based on the three capabilities. The paper presents an analytic and systematic approach for measuring the three capabilities and presents methods for assessing and benchmarking measured results. This should finally lead to industrialized applications which could provide recommendations enabling the company becoming a more efficient mass customizer.

Key Words: ***Framework, Assessment, Mass Customization, Capabilities, Solution Space Development, Choice Navigation, Robust Process Design***

1. INTRODUCTION

To address the increasing customer demand for personally customized products, Mass Customization, Personalization and Co-creation (MCPC) has been widely adopted as a competitive business strategy during the last two decades [1],[2],[3],[4]. Many companies have within the same period acknowledged that the implementation MCPC is much more complicated than immediately anticipated and in some cases even jeopardized the existence of the company instead increasing competitiveness. Of course others have shown the road to success like DELL, BMW, and ADIDAS [4]. Due to the large difference in success for companies implementing MCPC, analyses and method development has been addressed extensively in literature [5],[6].

In the article "Cracking the Code of Mass Customization" [4] the authors argue against the common executive perception of MCPC as a "fascinating but impractical idea", by introducing the concept of 3 fundamental capabilities as success factors, based on the results from substantial research of 238 companies in eight countries. The three capabilities required for successful implementation of MCPC are 1) Solution Space Development, 2) Robust Process Design, and 3) Choice Navigation [4]. The three capabilities are each supported by three approaches to achieve that specific capability (fig. 1.).

Solutions Space Development
Understanding customers' idiosyncratic needs
- Innovation Tool Kits
- Virtuel Concept Testing
- Customers Experience Intelligence

Robust Process Design
Reuse and/or recombine organizational resources to fulfill different customers' needs efficiently
- Flexible Automation
- Process Modularity
- Adaptive Human Capital

Choice Navigation
Supporting the customer in identifying appropriate solutions without getting confused
- Assortment Matching
- Fast Cycle trial-and –error learning
- Embedded Configuration

Fig. 1 *The three fundamental capabilities and approaches to develop* [4].

Each capability is described as a continuum i.e. a company can be extremely capable, not capable at all or anything in between in relation to each capability. A company being highly capable within each of the three capabilities could thus be considered the ideal mass customizer, whereas a company being less capable would indicate a mass production company not very capable of mass customizing. An example of mapping the three capabilities,is shown in figure 2. Identifying for which capability a company has the lowest performance (being least capable), would thus help the company identifying where to focus its effort to boost its chances of success in a mass customization market.

Since the publication of Cracking the Code of Mass Customization [4] several scientific publications have addressed how to improve each capability [7],[8],[9]. Prior to this a number of publications have also addressed these issues, although using different terms for similar concepts. [5],[6].

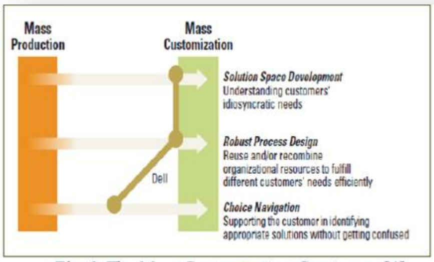

Fig. 2 *The Mass Customization Continuum* [4].

The approaches which are proposed in relation to "Cracking the code of mass Customization" are validated through intensive research [4],[10], but except the illustration of the MC continuum (fig. 2) [4] no guidelines are presented how to assess the capabilities in practice in a company. Furthermore, it is argued by [4] that there is not one magic bullet or a single quick fix which enables a high performance within each capability thus ensuring successful MC. Hence, it appears that it may be difficult for companies striving for Mass Customization to identify how to improve the capabilities, as no generic guidelines can be followed and an assessment is not immediately possible.

Based on case studies and surveys [10] it has been shown that gaining capabilities and thereby becoming a better mass customizer is done by small incremental improvements e.g. by using the approaches presented in literature. However, for incremental changes to be worthwhile, they must be focused at the right area, i.e. within the specific capability that has the greatest potential for improvement. Given that a company has limited resources to implement improvement of the three capabilities, the resources should be focused on the capability where an investment would yield the greatest effect on overall competitiveness. We hypothesize that the greatest effect would usually be within the capability where the company has the lowest performance. Referring to the Dell example in figure 2, an investment in developing capabilities would make most sense within choice navigation, since Dell has excellent performance within solution space development and robust process design. This is not saying that improving those capabilities would not at all be worthwhile, but it is likely that the relative improvement of overall competitiveness would be greater if focusing on choice navigation.

However, to be able to focus the improvement effort according to capability performance, companies must be able to assess how they perform within each capability and relate them to each other to establish a relative performance to prioritize improvement efforts. Since we have not been able to identify methods for assessing the capabilities, we assume that practitioners do not apply structured methods for capability assessment. It may on the other hand be possible that managers intuitively can tell which capability would yield the greatest potential for improvement, but that would rely on management experience and business insight rather than methodical analyses. This would imply that some companies would undoubtedly be able to confidently assess the performance within each capability and prioritize optimally, some companies would get lucky while others would fail due to lack of experience and insight. Following this we hypothesize that companies today are generally not able to assess their mass customization capabilities and a methodical tool for this would aid mass customizers in achieving competitiveness through mass customization.

1.1 Research question

The overall purpose of this paper is to analyze the need for mass customization capability assessment methods and contribute to enabling the measurement of mass customization capabilities to enable mass customizers to increase competitiveness. However, to be able to enable the measurement of the capabilities, it must be determined which variables can be used to measure these capabilities and how they are related. The main research questions of this paper are thus:

Q1: Are companies able to assess mass customization capabilities and prioritize improvement efforts accordingly?

Q2: Which variables can be used to explain the three mass customization capabilities and how are they interrelated?

1.2 Methods

Research question 1 will be addressed through three case studies. The case studies focus on three very different companies which are all moving towards mass customization but have chosen significantly different paths towards this goal. Each case is analyzed to qualitatively assess their capabilities within the three different areas and whether they are able to pin out which capability to focus on to achieve the greatest improvements. By doing this we can arrive at a conclusion whether assessing MC capabilities is a trivial task in industry.

Research question 2 will be answered by reviewing literature to identify parameters useful for measuring MC capabilities as well as the findings from the case studies will be used to identify how companies evaluate their MC capabilities. Once the parameters are identified, the relations between them will be identified and a summarizing framework will be presented, including the measurement parameters, their interrelation and their relations to the three capabilities.

2. CASE STUDIES

Each of following cases has been involved in mass customization in different levels of implementation and with different approaches to achieve the fundamental capabilities. None of the cases have been working towards mass customization following schemes like the systematic analysis of capabilities and prioritized efforts accordingly. The knowledge collected at these companies for the case studies has been collected in relation to individual projects with different objectives than what is presented in this paper. Because of that the cases are neither uniform in description nor in data.

2.2 Case 1

This case is about a company, developing, producing and selling truck lifting equipment, primarily in Europe. The company has through the last decade developed the company in different areas to increase its competitiveness, which could be expressed in MC terms. Solutions Space development is done primarily in an engineer driven traditional new product development department. As an approach to customer driven development the company has offered product development seminars for selected customers. Variants and new product platforms are enrolled into new products in predefined product management based on modular product structures, which are related to both production process capability and choice navigation capability. The production has undergone a change from line production into production cells based on lean and agile production philosophies. The production process and handling of variants are defined by the product structure and production documents are ideally automated produced based on selection made in the product configurator. The choice navigation is done from classic leaflets and brochure, supplied with matrix selectors for variants. To document the customer requirements an engineer controlled product configurator is used. The solution space is converted into spreadsheets which are used in the product configurator.

The company has through the last 10 years initial increased its market share and opened new markets, but through the financial crisis suffered loss on the bottom line due to loss in market share and smaller gross margin which seems to be derived from customization which is closer to *engineer-to-order* than *mass customization*.

2.3 Case 2

This case is about a company manufacturing work wear to the service sector, primarily to the northern European market. The company has during the last decade added market and gained new customer by moving from highly specialized customer order design to manufacturing based on modularized product design. The company has developed its new solution space in an internal design studio based on market research studies. Like most other actors within the apparel industries this company has sub suppliers in the Far East, with product structures, operations routes, and logistics which calls for mass production rather than going for mass customization. The process design has taken the manufacturing process from the Far East back to Europe, partly because of faster delivery and easier communication from entry of order to delivery. Choice navigation has been simplified to a leaflet working like the old fashioned paper doll toy, which in the end by help of a designer creates a unique documentation, within a predefined solution space.

The company has over the last 10 years increased its markets share but suffered also a decrease when the financial crisis hit their customers, they have since increased its market shares more than anticipated alone related to market development.

2.4 Case 3

A major pump manufacturing company, developing, manufacturing and selling in the global market is in the final steps of introducing the third generation of green domestic water pumps. As it is indicated there has been two generations of pumps prior to this, which has been marketed in a relative simple solution space (up 20 variants). The company's strategy behind new third generation derives from the green competition in the market and legislation for low energy consumption. Within a relative short period of time new product platforms have been developed and more efficiently manufacturing process's developed accordingly. Each generation has been developed with more and more customer involvement in the design process, even so the on market has decreased, because new need's has to be fulfilled, need's beyond the capable solution space, capable process's, and capable choice navigation. Each generation has been manufactured in an environment in a strong and robust process design, well defined solution space, and choice navigation which matches the other two capabilities. The first two generations defined with a fervent desire first of all to have optimum capability in the robust process design. The newest generation has once again focus on a robust process design which supports a more capable solution space which over time can expand to customer's needs. The robust process designs are expressed in a full automated manufacturing line which is scalable in volume of production and accepts a large variety, beyond the initially defined solution space. The product itself furthermore has embedded configuration.

These products are the core products and one of major income for the company, which makes improvements essential for the survival of the company.

2.5 Case Discussion

Common for what was observed in the three case companies is that they are all moving toward mass customization, however using different approaches. None of the companies had an explicit strategy for balancing the effort between the three MC capabilities and certainly not a structured approach for assessing their capabilities.

Based on these cases and other cases from literature it is argued that a common or generic framework to assess the customization level is needed. It is argued that such framework should cover assessment of three capabilities with comparable scores, levels, numbers, and/or datasets. Ideally this should be based on common data or data easily produced in a company, making it possible to make benchmark internally as well as externally too.

Measuring a capability is not a matter of just dipping the thermometer and reading the numbers, as well as being a mass customizer is not a matter of a single decision or single action[4],[11]. Based on above case studies it is argued that measurable expressions of the three capabilities need to be established.

3. MEASURABLE CAPABILITY PARAMETERS

In the literature controllable and analyzable parameters can be identified as KPI's and standardized variables often related to the financial reporting. Financial reporting is used as periodical status for public interests and as an instrument used by investors [12]. Standardized financial reports are characterized by explicit data (parameters, variables, and numbers) all comparable across companies and industries, which make them useful in indexing capabilities if it is possible to establish relationships or correlation between financial reports elements and capabilities, in this case the three MC capabilities. Other research has revealed in depth analysis and models of how relationships of processes in a mass customizer company could be expressed, this work has led to models of "Key Metrics Systems for variety Steering in Mass Customization" [13],[14],[15],[16],[17]. The models are based on MC sub processes and in relation to each process parameters and calculations behind these parameters are suggested. Both the standardized financial report and the *Key Metrics System model* are used as basis for further analysis of potential parameters to measure *the three fundamental capabilities*.

3.1 Standardized Financial Report Parameters

Building relationships between Standardized Finance Reporting parameters or variables and *the three fundamental capabilities* does not reveal any explicit relationship or correlation useful for, analyzing, or measuring the company's status as mass customizer (see table 1). Because of its nature as a summarized statement (standardized following international agreed procedures) in each of the financial standardized parameters it is possible to establish relationships to all three capabilities for each parameter.

Table 1. *Relationships Standardized Financial Report and the three capabilities in mass customization.*

Standard Finance reports (ref IFRS)	**MC**		
	SSD	RPD	CN
Sale of Goods			■
Cost of Sales		■	■
Gross Profit			
Selling and Distribution Cost		■	■
Administrative Expenses	■	■	■
Other Operating Expenses	■	■	■
Operating Profit			
Finance Cost	■	■	■
Finance Income			
Profit before tax			
Tax			
Profit			

Nevertheless each parameter has underlying detailed specifications with data which can be related to specific capabilities. A financial report can be analyzed into more detailed figures and KPIs by using financial ratios and other financial analytic tools. Examples of these are DuPont model (fig. 3), ABC-model or similar or by decomposing International Standardized Financial Report using International Accounting Standards [12].

An example is Sales of goods are related to Choice Navigation, ideally sales are selection of specific variants which fulfill the customers' needs, as assortment matching or fast-cycle, trial-and-error-learning processes which are IT supported often as product configurators, guided selectors etc.

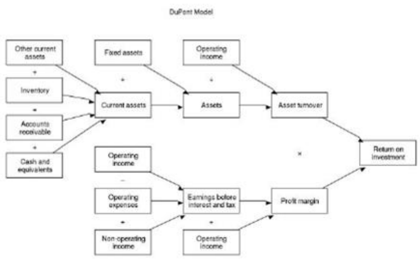

Fig. 3 *Examples of detailed parameters or variable useful as indicators to assess status of mass customization if relationship to the thre capabilities ca be established.*[11]

3.2 Key Metrics System parameters

Through literature review the *Key Metrics System model* has been delimitated as the one of the best candidate to deliver useful parameters, measurable parameters, and validated parameters within the mass customization processes [17]. The *key Metrics System model* has been presented and developed as a means to variety steering in mass customization. Research for the *Key Metrics System model* (figure 4) has been based on reviews of different approaches to mass customization, which not only strengthens the validity of the parameters for use in a framework seeking measurable parameters within mass customization, but have roots to almost all relevant research in the domain, too. In table 2 the relationship matrix indicating correlation between parameter used in the *key metrics system model* and the three capabilities.

Opposed to the standardized Financial Report it seems that at high level *Key Metrics System Model parameters* explicit can be identified as good candidates as measurable parameters for *the three fundamental capabilities*. Further analysis of the *Key Metrics System model* reveals further detailed calculable parameters all on a basis common accepted KPIs.

As an example the Used Variety [17] can be explained as the perceived variety compared to the theoretically possible variety; a number between 0 and 1 and theoretically simple to calculate.

A low number indicates that product variants could be uninteresting or may not be perceived by costumers [17], which could either be related to ineffective Solution Space Development or inadequate Choice Navigation. In this example *Innovation toolkit* as an approach could be the answer to improve the capability Solution Space

Development or Assortment matching software to improve Choice Navigation.

Table 2. *Relationship Key Metrics System parameters and the three fundamental Capabilities for Mass Customization. (Modified from* [16] *(fig. 17, pp. 17)*

Key Metric System elements	MC cap		
	SSD	RPD	CN
Product Architecture	■		
Web appearance and data format			■
Used Variety	■		■
Components Commonality	■		■
Production Process Commonality		■	
Purchasing Process Commonality	■	■	
Modules Suppliers Weight	■	■	
Setup Duration			■
Potential Customer Happiness			■
New Customers Base	■		■
Repurchase	■		■
Sales			■

correlation or relationship between *the three fundamental capabilities* and accepted models, models, and tools for business models has been sporadic and much of that research have been done before a general acceptance of *the three fundamental capabilities* and the correlated approaches was presented in 2009. *The three fundamental capabilities* and the related approaches to achieve the capabilities are the backbone for the work to establish a framework to assess *the three fundamental capabilities* for mass customization. The well placed criticism in doing that is a matter of "are these three capabilities for mass customization enough fundamental to be the only ones?" – Probably not, but for this work it has been marked as sufficient. Of course other and probably fundamental capabilities to run a general business are needed in a mass customization business, but solely to aim for mass customization *the three fundamental capabilities* are covering the needs.

The case studies behind this work have revealed that a framework should cover assessment of three capabilities with comparable scores, levels, numbers, and/or datasets. Ideally this should be based on common data or data easily produced in a company, making it

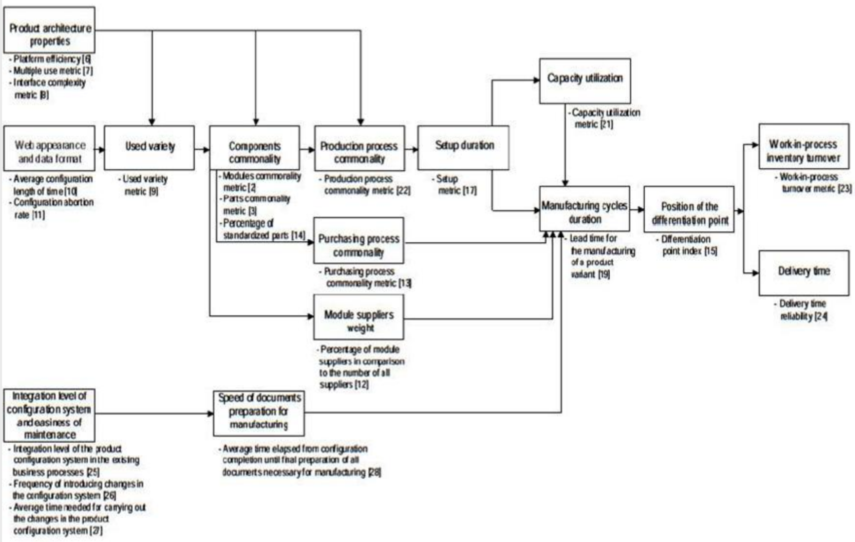

Fig. 4 *Key Metrics System model* [15]

4. DISCUSSION AND CONCLUSIONS

Establishing a framework to assess *the three fundamental capabilities* could be a way to keep the industry staying in business and aiming further for mass customization. It has been recognized that at least 20% of MC startups leave business within 12 months [18]. It seems that even though it has been recognized that the three capabilities are fundamental[3],[11],[19], the research in models, methods, and tools describing the possible to make benchmark internally as well as externally too.

It has been found that measuring capability is not a matter of just dipping the thermometer and reading the numbers. Furthermore, other works indicate that establishing capabilities is not a matter of a single discussion or single action by management, but requires continuous attention by management as other strategic processes [4],[11].

Establishing assessment data or gain knowledge about and have well the mass customization process are working, cannot be established alone by analyzing a company's financial report. A relationship matrix has been established but reveals little explicit information which could be related to individual capabilities. An example of the difficulties in using the financial report as assessment alone is: *the variable cost of production*, which is the financial result of involved manufacturing processes, including related or accumulated direct product related variable cost coming from process design like flexible automation or process modularity and sales systems setup as running cost of IT-systems for configuration or web-sale-services[12], of which all are related to both Robust Process Design and Choice Navigation[4].

A relationship matrix between *key metrics system model parameters* and *the three fundamental capabilities* indicates that specific equations, datasets, and/or number can be correlated or related to specific capabilities.

It has been indicated that it is necessary to establish a framework to assess *the three fundamental capabilities*. This indication is based on information gathered from three cases describing companies approaching the mass customization process with different strategies and management engagement; even though it is argued that they are working blindfolded and have nothing or in best cases small indication whether their efforts bring them closer to a better business based on mass customization. The work indicates that a framework to assess the mass customization process can be established analyzing standard financial reports using standardized and accepted methods and tools and by analyzing using equations and data, based on *key metrics system model parameters*.

Future work should address establishing tools to assess the individual performance within *the three fundamental capabilities*. Additional work has been done to exemplify how to establish knowledge about variables and parameters useful to assess Solution Space Development, this work is presented in the paper "Solution Space Assessment for Mass Customization"[20].

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Paper 6

Solution Space Assessment for Mass Customization

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SOLUTION SPACE ASSESSMENT FOR MASS CUSTOMIZATION

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Abstract:
In mass customization, the capability solution space development is essential to offer a variety of products which satisfies the idiosyncratic needs of the customers. We argue that there is a need for methods which can assess a company's solution space and their capability to develop it. Through literature study and analysis of solution space characteristics a number of metrics are described which can be used for solution space assessment. They are divided into five caterories: Profitability, Utilization, Variety Demand satisfaction, Architecture and Responsiveness. The metrics and be applied as KPI's to help MC companies prioritize efforts in business improvement.

Key Words: ***Mass Customization, solution space development***

1. INTRODUCTION

In any company it is essential to offer products which match the needs and desires of customers to achieve sales and profit. This is true for mass producers as well as mass customizers; however in mass customization this issue is somewhat more complex than mass production due to a much higher variety and a more complex product structure. As pointed out by Salvador et al., mass customizers need three fundamental capabilities to be successful: 1) Solution Space Development – Identifying the attributes along which customer needs diverge, 2) Robust Process Design – Reusing or recombining existing organizational and value chain resources to fulfill a stream of differentiated customer needs and 3) Choice Navigation – Supporting customers in identifying their own solutions while minimizing complexity and the burden of choice [11,17].

In order for companies to be able to establish themselves as mass customizers or for existing mass customizer to improve performance, it is proposed that a set of methods for assessing the three capabilities is developed. In this paper, the focus is solely on the capabilities for solution space development. The research question for this paper is: What parameters can be used to assess capabilities for solution space development and how can these be determined?

The solution space is a definition of which combinations of configuration variables are offered to customers corresponding to features, options or module selection. According to Salvador et al. solution space development is a matter of identifying the idiosyncratic needs of the customers and delineate what products will be offered and which will not, or put in other words, which customer needs to meet and which not to meet [17]. The goal of solution space development should be to develop an optimal solution space. However optimality can be with respect to a number of different criteria, e.g. maximum accumulated profits, satisfying the most customers' demands or minimizing the variety. It is thus not trivial to determine what the optimal solution space is.

2. SOLUTION SPACE DEVELOPMENT

Salvador et al. presented a number of approaches to develop these capabilities, which were 1) innovation toolkits, 2) virtual concept testing and 3) Customer experience intelligence [17]. However, these approaches are methods for developing the solution space rather than assessing the solution space.

Two different perspectives are relevant when assessing a company's solution space development capabilities. The first perspective is concerned with assessing the capabilities for conducting the process of defining the solution space, i.e. a process view. The second perspective is concerned with how well the solution space serves its purpose, i.e. an analysis of the result of the solution space development. The two perspectives are closely linked, meaning that if a company has a good capability of developing the solution space, they are very likely to have an appropriate solution space. In the following, we assume that a company's capability to perform solution space development can be assessed by assessing the result of this process, i.e. the solution space.

2.1 Marginal view

To describe the mechanisms of solution space development, we take a marginal view, i.e. describe what happens when new variety is introduced into a solution space by e.g. offering a new option which customer can choose. Ideally introducing new option will lead to products being sold including this option thus increasing turnover by either increasing the number of products sold or by being able to charge a higher price for those products sold including that new option. However all new options cannot be equally successful and some will inevitably lead to greater increase in sales than others.

On the other hand, introducing a new option comes at a cost. This cost may include product development, implementation in product configurator and other IT systems, tool preparation and additional manufacturing cost. Obviously, for the introduction of the new option to be successful the increase in turnover should at least exceed the total costs of the introduction.

Unfortunately, it may not be trivial to calculate the true profitability of the introduction of a new option due to a number of factors. First, it is quite difficult to calculate or even estimate the actual cost of introducing a new option, especially on beforehand if using it as a decision tool. Secondly, it is obviously also difficult to predict the sales of a new option, not only because of the difficulties of forecasting the sales volume, but also because introducing a new option may cannibalize other options, which are then rendered less profitable. This could be the case if an option is introduced which is practically indistinguishable from an already existing option. This could lead to figures indicating that the new option is seemingly profitable but at the expense of other options potentially leading to sub optimization of the solution space.

2.2 Solution space sets

In order to establish metrics for solution space development and developing measurement techniques, it is important to have some sort of idea of what constitutes a "good" solution space or even an optimal solution space.

The optimality of a solution space can be described by defining two sets of products: 1) the different products offered by an MC company, defined as the set SS (Solution Space) and 2) the variety of products which are demanded by the customers, defined as the set CDV (Customer demanded variety). As illustrated in figure 1, the intersection of the two sets will represent the products offered by the MC company which correspond to products demanded by customers. The intersection of the two sets thus represents the products that customers may buy, given they are able to find and configure the products and willing to pay the required sales price.

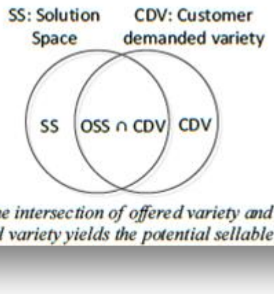

Fig. 1. *The intersection of offered variety and customer demanded variety yields the potential sellable products.*

Intuitively, maximizing the set SS∩CDV would seem like a good idea since this would maximize the potential number of product variants that can be sold to customers. However, one must bear in mind that all variety comes at a cost and attempting to satisfy each and every customers demand for variety can lead to soaring costs in relation to product development, manufacturing cost and sales costs.

It would also seem intuitive that the set SS \ CDV i.e. products which are part of the offered variety but are not demanded by customers should be minimized or even eliminated. This is partly true since these products are per definition not sold and will thus not contribute to turnover. However these variants may be combinations of other variables which are demanded by customers and do thus not induce additional cost, implying that removing this variety would potentially be more expensive than keeping it.

When describing the solution space as set, it should be defined which elements are in the set. As presented above, each element in the sets will correspond to a unique product variant. Following this, each possible combination of configuration choices would correspond to a variant and thus an element in the set. However, for most MC product families, the number of elements becomes astronomical due to numerous configuration variables each with a number of outcomes. For example, when configuring a Mini Cooper online the configuration choices presented to the customer will result in a number of possible variants well above a 20 digit figure. This is obviously significantly more than the potential market of the Mini Cooper. Assuming that the sale of Mini Coopers is a good representation of the demanded variety, and the Mini Cooper has sold a few million cars and assuming that each sold Mini Cooper is unique, the customer demanded variety will only be a tiny fraction of the offered variety and as a consequence. Furthermore we would expect that assessing whether single variants would counter a demand from a customer is simply not possible if the number of variants is high. Thus it would seem that variants defined as all possible combinations of configuration variables is not an appropriate way to define the solution space set as well as assessing the intersection of SS and CDV.

2.3 Solution space representation

A more simple and comprehensible way of representing the sets may be defining the elements of the sets as the "dimensions of customization". If a product has a number of customizable attributes and each attribute has a finite number of values that can be chosen, each value will correspond to a product property which can potentially be demanded by a customer. Figure 2 illustrates the definition of solution space set and customer demanded variety set, using a fictive example of a customizable shirt, where three different colors, four different sizes and two different sleeve lengths can be customized. Each element in the set SS corresponds to one value of a customizable attribute, e.g. the attribute "Color" having the value "Blue". In this example the color red is contained in the solution space set but not in the customer demanded variety and is thus unnecessary variety increasing costs without increasing sales. The element representing the attribute "Size" with value "x-small" is contained only in the set CDV and is thus not offered by the current solution space. This implies that there is an unfulfilled customer demand which could be satisfied by extending the solution space thus increasing the customer base. Obviously the elements in the intersection of the two sets represents customer demanded attribute values which are fulfilled by the current solution space, and no action is seemingly required.

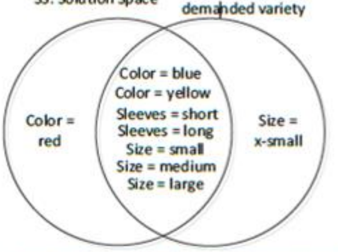

Fig. 2. *Example of definition of solution space set based on attribute values*

If the example presented in figure 2 were reconstructed defining each element as a unique combination of customizable attributes, the set SS would contain 18 elements instead of 8. If an extra customizable attribute were added with two possible values, this figure doubles. Generally the size of the set will increase exponentially when adding customizable. Using the approach illustrated in figure 2 the sets grow linearly when customizable attributes are added. Returning to the example of the Mini Cooper, representing the solution space by possible attribute values would lead to a set of less than 100 elements rather than the 20 digit number of possible combinations.

We thus propose that the solution space is described by the number of customizable attribute's values. Defining the solution space this way is trivial, since an MC company's offerings will usually be explicit in a configurator, product family model or other documentation. Defining the set CDV on the other hand is far more difficult since it will be impossible or at least extremely time consuming to clarify all potential customers' demand for variety. Also this would depend on the delimitation of the product family's intended customer base. As a result, measuring the size of CDV will expectedly be practically impossible.

As mentioned previously, whether an attribute value is in the intersection of the two sets or only in one of them would indicate an action, however this is not necessarily true. The reason for this is the fact that all customizable attribute values are not likely to be subject to the same demand. Hence some attribute values will be sold very frequently while some are perhaps rarely sold. In the case where an attribute value is rarely sold, addressing the solution space as a simple set would conclude that the attribute value is demanded by customers and should thus be included in the solution space. However due to lack of volume the cost of producing the product corresponding to that specific attribute value may exceed the sales price of the product.

This indicates that viewing the solution space and customer demanded variety alone is not sufficient to assess the optimality of a solution space. This must be supplemented with a measure of e.g. how frequently a certain attribute value is demanded and preferably whether offering that specific attribute value is profitable. For the elements present in the intersection of SS and CDV this could be possible since historic data is present to analyze. However, for elements not previously part of the solution space but are considered by a company to include in the solution space due to recognition of a demand for variety, this assessment is more challenging. This is due to the fact that the assessment must be based on predictions of the future which are inherently uncertain. On the other hand, if this assessment could be performed, it would enable mass customizers to make qualified decisions regarding the development of their solution space.

2.4 Requirements for solution space assessment

Concluding on the considerations above, we propose that it would be beneficial for mass customizers if an assessment of the solution space could be performed. This assessment should be able to measure the "utilization" or "efficiency" of the solution space as well as the profitability.

However, assessing the utilization of profitability of a certain solution space provides only a snapshot of the current state of a company's offerings. Recognizing that today's markets are ever more rapidly changing, it is relevant also to evaluate the responsiveness of a company related to the solution space development, i.e. how fast and efficient is a company able to change its solution space according to new market demand. This could either be a new customer demand for variety that needs to be recognized, developed and offered through the sales channels as fast as possible. On the other hand, it could be the disappearance of a customer demand for variety caused by internal or external factor. This could be legislation, competitor offerings or new products within the company's own product portfolio which significantly reduces or completely removes the demand for a particular attribute value ultimately rendering it unprofitable to offer that option. This attribute should naturally be removed as fast as possible to avoid economic loss and the pace at which this happens indicates a different form of responsiveness. One other factor relevant to assessing the dynamics of solution space development is the cost of developing the solution space, i.e. how much does it cost to introduce a new attribute value.

Hence, in order to assess a mass customizer's capability it will also be relevant to address these different types of responsiveness apart from the current state of the solution space.

In the following section the literature within mass customization has been reviewed to identify possible methods for solution space assessment.

3. LITERATURE REVIEW

Desmeules analyzed the relationship between the variety perceived by the customer and the customer happiness [4]. Of course increased variety provides increased customer happiness to some extent, however due to a number of factors, once the variety reaches a certain level, the increase in customer happiness levels out and eventually drops. In figure 3, this relationship is illustrated as an inverted U shape. The mechanisms that create the upward slope, thereby increasing customer happiness are well known and proven in MC literature. The point where increased variety levels starts reducing customer happiness is however very interesting for companies, since this would indicate some sort of variety optimum for a solution space. The reasons for the downwards slope are that the number of choices become overwhelming and the customers ability to self regulate the process fails resulting in frustration and indeed reduced customer happiness.

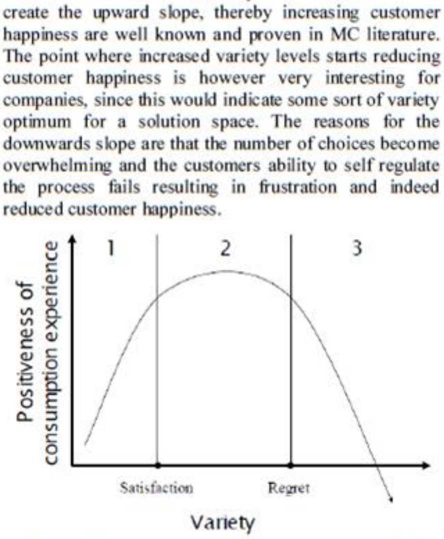

Fig 3. *Relationship between perceived variety and positiveness of consumption experiences* [4].

Desmeules suggests that increased customer knowledge about product characteristics would cause the point where customer happiness drops to shift to the right, which seems reasonable. This implies that better information during the sales process would allow utilizing a higher product variety.

Rathnow [16] also proposed that the benefits of increasing variety seizes at some point, although he does not suggest an actual drop in customer benefits. However the costs increase exponentially as the variety is increased. This is illustrated in figure 4, where it is suggested that the difference between cost and benefits, both functions of the variety, defines the benefit overplus. The optimum variety is defined as the degree of variety where there is the greatest difference between cost and benefit referred to as the maximum benefit overplus. However, this is only conceptually described and is thus difficult to apply in practice unless the benefit as a function of variety can be quantified.

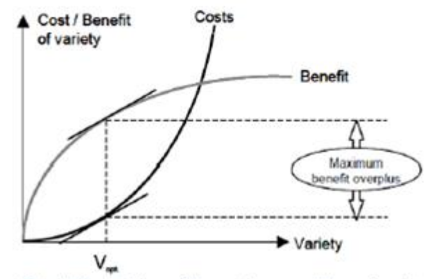

Fig. 4. *Description of the optimum problem of variety. Original source* [16], *reproduced from* [2]

Hichert [8] (referred from [2]), defined the effects on manufacturing cost from increasing product variety. He described that increased variety brings along higher unit costs due to increased manufacturing complexity, however some of these increases in cost are not reversible by reducing variety. This is due to investments in e.g. building, IT systems, machines etc, which cannot simply be sold off without a loss if the variety is reduced and the manufacturing complexity is sought reduced. This leads to a cost remanence, which is the difference between manufacturing costs prior to and after an increase and decrease in variety as illustrated in figure 5.

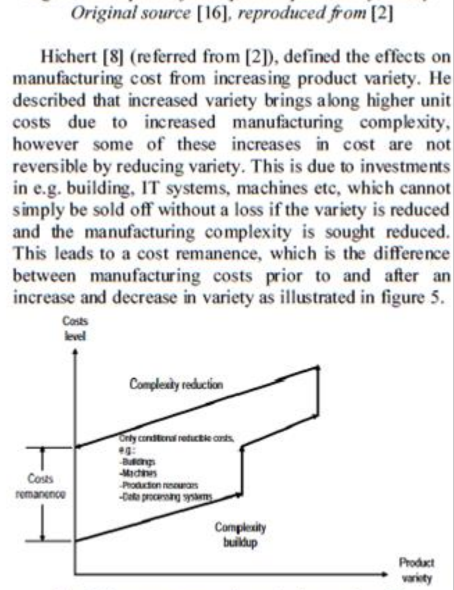

Fig 5 *Costs remanence by reducing variety* [8], *Reproduced from* [2].

This emphasizes the need for solution space development capabilities in mass customization, since wrong decisions about increasing variety may lead to irreversible negative consequences.

Piller et al. developed a model of the economy of mass customization and customer integration [15]. Increased variety will increase the customer willingness to pay price premium for a customized product. However increased variety usually implies increased costs in relation to manufacturing but also transaction costs due to a more intensive customer interaction in the sales phase. The increased costs can according to Piller et al. be countered by the principles of MC e.g. modular products, flexible manufacturing, IT system etc. However apart from this, the term "Economies of Customer Integration" is introduced, which are additional mechanisms which can counter increased costs. These include: 1) postponing some activities until an order is placed, 2) more precise information about market demands and 3) The ability to increase loyalty by directly interacting with each customer. When developing a solution space it is thereby relevant not only to balance sales volume with manufacturing costs but also take the mechanisms of "Economies of Customer Integration" into account.

Gu et al. presented an optimization method for MC products which seeks to maximize the manufacturing efficiency [7]. This model suggests increasing the commonality on different BOM levels and thereby maximizing the number of "mass production steps" and minimizing the customization steps during the manufacturing process. While this model would help in improving manufacturing efficiency given a certain set of functional requirements, it does not address balancing the customer demand for customization with the manufacturing efficiency.

Kumar formulated a number of metrics for customization, mass production and modularity, thereby measuring the number of modules, combinations and theoretical production volume per module. The main metrics were: 1) average number of options per feature, 2) Maximum number of configurations 3) average number of configurations per customer 4) Degree of customization and 5) average demand per option per period [10]. These metrics are useful in relation to describing the variety of a product family, however less useful in relation to assessing whether some options are configured less frequently than others potentially rendering them less profitable. Furthermore, these methods do not enable assessment of whether the variety offered is actually the variety demanded by customers.

Syam and Kumar [18] analyzed the relationship between standard goods, customized goods and competing products to clarify the effects of offering customized products. They concluded that it may be beneficial for a company to offer a mix of standard and customized products, to satisfy different segments. This point is essential in relation to solution space development, since standard products can be offered to special segments to achieve overall optimality of the solution space. The paper however uses synthetic models to evaluate their hypotheses and provides thus no practical guidelines for assessing the solution space consisting of customized and standard products and do also not provide general guidelines for defining which products should be sold as standard and which should be sold as customized products.

Several authors approach the design problem in developing MC products effectively by quantifying customer value and estimating product cost [9], [12],[6]. However, none of these are found to provide metrics which are useful for assessing an existing solution space.

Gu et al. [7] present an optimization method for mass customization, primarily through standardization, but does not take into account the relationship between customer demand and the offered variety.

Blecker et al. [1] presented an extensive system of metrics for variety steering which is probably the most usefull work in relation to identifying metrics for solution space development. Based on a sub-process model representing the essential sub-processes of mass customization a number of metrics are identified to form a system able to assist in making decisions regarding variety. Hence the work aims at providing a tool for solution space decisions rather than providing an assessment, however several elements can be adopted to that purpose. The identified metrics are related to four different "zones": 1) customizable attributes, 2) product architecture and configuration system, 3) variety driven internal complexity and 4) customers and sales. The specific metrics that are considered relevant for assessing the solution space are:

- Platform efficiency metric [13]
- Multiple use metric [5]
- Interface complexity metric [5]
- Used variety [14]
- Modules commonality metric
- Parts commonality
- Percentage of standardized parts
- Number of new introduced customizable attributes during period ΔT
- Number of eliminated customizable attributes during period ΔT
- Customer churn rate at ΔT
- Growth rate
- Repurchase rate
- Sales
- Configuration abortion rate

Each of these metrics are linked closely to the solution space and will be affected when changing the solution space. Some of the metrics are indeed influenced by the solution space but not exclusively, meaning that they are influenced by other factors. One example is sales, which would be influenced by seasonality, market trends, marketing effort etc.

3.1 Conclusions from literature

From the literature above, it can be concluded that several authors have developed different ways to describe the solution space in Mass Customization. Some have addressed this conceptually, which points out specific areas to measure. However, few have addressed the issue of assessing the performance of a solution space and the capability to develop it.

We have not been able to identify any literature which has described practical guidelines for assessing a solution space as well as examples of implementation are absent. However, a few publications provide metrics which seem to be applicable for assessing a solution space. These are in particular those presented by Blecker et al. [1] and Kumar[10]. However, compared to the issues presented in section 2.4, additional metrics will need to be developed. In the following section, a list of relevant metrics from literature and new metrics will be presented.

4. METRICS FOR SOLUTION SPACE ASSESSMENT

The metrics for assessing a company's solution space as well as their solution space development capabilities need to reflect the requirements described above. Furthermore metrics need to be measurable; otherwise they are per definition not metrics. This means that for each metric, the required data should preferably be readily available in the company or should be easily obtainable. Luckily, most MC companies have information systems which could support this, such as configurators, Product Lifecycle Management (PLM) systems, Enterprise Resource (ERP) systems, Engineering Change Management (ECM) systems etc., which we expect would provide most of the required data.

The metrics are divided in five categories depending on what they are intended to measure. These categories are shown in figure 6 and described in the following along with the specific metrics.

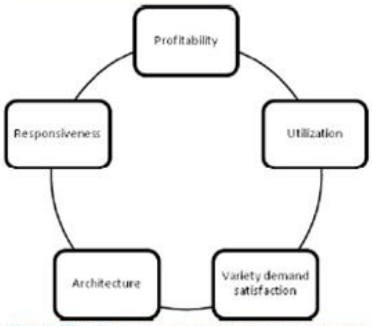

Fig. 6. *The five categories introduces to measure Solution Space.*

4.1 Profitability

Within this category, the authors have identified no metrics in the literature. What this category of metrics is supposed to measure is how profitable the mass customized products are. The reason this should be measured is the assumption that the capability for solution space development is a prerequisite for being a successful mass customizer, i.e. profitable mass customizer. Hence, a profitable product portfolio will indicate a well developed solution space. The following metrics are defined:

Aggregate solution space profitability (**ASSP**) is a measure of how profitable the solution space is as a whole and should be measured over a period of time:

$$ASSP = \textit{Total Sales income} - \textit{Total manufacturing cost} \quad (1)$$

We propose to also introduce a metric measuring profitability per product family (**PFP**), calculated similarly over a period of time. This however sets additional requirements do data availability, as manufacturing costs must be registered more detailed:

$$PFP = \textit{Sales income from product family} - \textit{manufacturing cost for product family} \quad (2)$$

We also propose a metric for Configuration Variable Profitability (**CVP**), which is somewhat less trivial to determine. However if historical configuration data is available with sales price and manufacturing costs registered for each configuration it is possible to generate a linear model describing the variation in price and cost from the configuration variables using the methods described by Brunoe & Nielsen [3]. From the significance and coefficients for each variable, it will be indicated if a specific configuration choice is profitable, e.g. a specific color. However assessing each variable may be useful in solution space development choices but less useful in assessing a company's overall capability, since it will consist typically of hundreds of figures, corresponding to the number of configuration options. However, once the profitability for each option is calculated, the distribution of profitabilities may be analyzed. What is interesting here is how many configuration variables (percentage) have negative profitability (**NPCV**). Obviously, this figure should be as low as possible, and will indicate how well a company is able to develop only configuration choices which are beneficial.

Furthermore we propose a metric for the skewness of the distribution of profitability (**CVPS**). A positive skew will indicate that a few configuration variables are very profitable, whereas a negative skew would indicate that a number of configuration variables contribute significantly to a lower profitability.

All of the data required to calculate the metrics defined within this category are usually obtainable from a company's configuration system and ERP system

4.2 Utilization

This category addresses how well the solution space is utilized by the customers, i.e. how much variety is offered vs. how much does actually make sense compared to the customers' requirements. This is what the metric defined by Piller [14] (referenced from [1]) called Used Variety (UV) is intended to measure:

$$UV = \frac{\textit{Number of perceived variants}}{\textit{Number of all possible variants}} \quad (3)$$

However, using this metric may be difficult in practice, since the number of perceived variants is not readily available. A more practical way of assessing the utilization would be to calculate the frequency by which each configuration variable is chosen by a customer. By dividing this by the frequency of which configurations are made in general, the percentage of configurations containing a certain configuration choice could be calculated, thereby describing the utilization of a certain configuration variable. If these percentages are analyzed statistically, two metrics can be derived: Mean Configuration Variable Utilization Percentage

(**MCVUP**) and Configuration Variable Utilization Percentage Variance (**CVUPV**). These two metrics can provide insight into the magnitude and differences in frequently by which certain parts of the solution space are actually creating value for customers.

4.3 Variety Demand Satisfaction

Measuring to what extent the variety offered by a company satisfies the demand for variety is very difficult to measure directly, since this would require immense amounts of data and possibly large customer surveys. However, Blecker [1] presented a number of metrics that are influenced by how satisfied customers are with the variety offered:

Sales are intuitively a metric that can be used to indicate how happy customers are with the variety offered by a company. However, sales can be influenced by many other factors than the solution space, e.g. marketing efforts, sales processes, pricing decisions etc. We do however believe that it can give some kind of indication.

The metric Repurchase rate (**RR**) [14] describes to what extent customers repurchases a product, or to what extent customers return to the MC company to buy another product. If customers repurchase products regularly, it is reasonable to assume that those customers have been happy with the variety and the product in general. Otherwise they would likely have chosen a competing product instead. The repurchase rate is defined as:

$$RR = \frac{number\ of\ repurchases}{total\ number\ of\ purchases} \quad (4)$$

A high repurchase rate can be interpreted as an indicator for high customer satisfaction with the product offerings, including variety. Clearly, the repurchase rate does only make sense for products which are purchased frequently, e.g. customized muesli or shirts, whereas products like cars or houses are purchased less frequently by the same customer, rendering this metric irrelevant.

The metric configuration abortion rate (**CAR**) [1] can also be a measure of how satisfied the customers are with the offered variety. Configuration abortion rate is defined as:

$$CAR = \frac{number\ of\ aborted\ configurations}{number\ of\ initiated\ configurations} \quad (5)$$

If a customer initiates a configuration and is not able to select the desired product properties, and is thus unsatisfied with the offered variety, that customer is likely to abandon the configuration and purchase a competing product. Hence, a high abortion rate could indicate that customers are dissatisfied with the offered variety and vice versa.

4.4 Architecture

The product architecture is very central in solution space development, since a good product architecture will greatly reduce development and manufacturing costs when increasing variety, whereas a suboptimal architecture will imply rapidly increasing costs when increasing product variety. Simply put, the product architecture allows efficient generation of product variants and this also indicates how efficienct a company is at solution space development.

Covered extensively in literature, several relevant metrics were found in the literature review. The multiple use metric (**MU**) indicates how many modules are required to produce all variants within the solution space [5]. This metric is defined as:

$$MU = \frac{NV}{NM} \quad (6)$$

NV is the number of product variants required by customers and NM is the number of different modules required to build all variants in the product portfolio. While number of different modules should be easy for any company to determine, the number of variants required by customers is less trivial. Instead of using this figure, the theoretical total number of product variants could be used. However, as mentioned previously in this paper, this figure may soar to astronomic numbers, rendering the metric less useful.

The modules commonality metric (**MCM**) [1] is a measure of how many modules are common to all variants relative to the total numbe of different modules. This metric is defined as:

$$MCM = \frac{Number\ of\ common\ modules}{Total\ Number\ of\ different\ modules} \quad (7)$$

Generally a higher module commonality will indicate a more efficient product architecture, since higher commonality will usually imply lower manufacturing and development costs. A metric for parts commonality (**PC**) [1] is used to measure the relationship between common parts and the total number of different parts in the same way as the module commonality metric. A high part commonality also indicates an efficient product architecture since that would imply higher purchasing volume for each different part further implying lower purchasing costs.

In most mass customization companies, these metrics should be trivial to calculate as the necessary data should be available in product documentation and the ERP system.

4.5 Responsiveness

The metrics within the responsiveness category are intended to measure how fast a company is able to develop its solution space e.g. in response to changed market requirements. The first metric is the rate of which new configuration attributes are introduced (**RNCA**). This is determined by summing up the number of added configuration choices during a certain period. Similarly, the number of eliminated configuration attributes should be measured resulting in the metric (**RECA**). A high RNCA indicates that a company frequently introduces new options for customers and would indicate that the company reacts to a broad spectrum of changes in the market. A large difference between RNCA and RECA would indicate that the solution space is either growing or shrinking. A steadily growing solution space could indicate a problem, since the company may be focusing on introducing new variety without doing "housekeeping" and eliminating options not needed anymore. This could result in unnecessarily increasing manufacturing complexity.

The two metrics described above describe the change rate of the solution space, but not the lead time for changes, which is also essential when competing in a rapidly changing market. We therefore introduce a new metric called average lead time for configuration variable changes (ALCVC). This metric is defined as the time from a the need for adding or removing a configuration variable is recognised until it is fully implemented. Ideally this metric should indicate the time from an external factor in fact changes until the response in form of a change in the solution space is implemented. However, since data is needed to calculate the value of the metric, in practice the time is measured from the change request is registered in e.g. an ECM or PLM system until it is fully implemented. Hence the time from an external factor changes until this is recognized and registered in e.g. an ECM system is not included in this metric.

5. CONCLUSIONS & DISCUSSION

Based on an analysis of the characteristics of an optimal solution space requirements were formulated to establish a number of metrics for assessing a solution space and companies' ability to perform solution space development. To establish these metrics, relevant literature was reviewed and several applicable metrics were identified. Further metrics were developed in areas where no sufficient metrics could be identified in literature. The following list compiles the identified and newly defined metrics within five areas:

Profitability:

- Aggregate solution space profitability (ASSP)
- profitability per product family (PFP)
- configuration variables (percentage) having negative profitability (NPCV)
- Configuration variable profitability skewness (CVPS)

Utilization

- Used Variety (UV)
- Mean Configuration Variable Utilization Percentage (MCVUP)
- Configuration Variable Utilization Percentage Variance (CVUPV)

Variety Demand Satisfaction

- Sales
- Repurchase rate (RR)
- configuration abortion rate (CAR)

Architecture

- The multiple use (MU)
- modules commonality (MCM)
- parts commonality (PC)

Responsiveness

- rate of which new configuration attributes are introduced (RNCA)
- number of eliminated configuration attributes (RECA)
- average lead time for configuration variable changes (ALCVC)

It is the intention that these metrics can be used to in MC companies for different purposes. One purpose is benchmarking against "best practice" mass customizers, in order to identify areas with the greatest potential for improvement. Another purpose is to use these metrics as key performance indicators which are continually calculated to monitor performance to continuously improve.

In relation to research in mass customization it is the intention to apply these metrics in different types of mass customization companies to analyze what distinguishes successful mass customizers.

It is evident that the application of these metrics poses certain requirements related to data availability and quality. However, most MC companies already have systems in place which are very likely to contain the data required for calculating the metrics presented in this paper.

As mentioned in the introduction, solution space development is one of three fundamental capabilities for successful mass customizers; the other two being robust process design and choice navigation. There are strong relations between these three capabilities, and phenomena experienced in a company cannot necessarily be attributed to only one capability, and as such, the metrics defined in this paper can also be influenced by other factors than the solution space development capability. If for instance the profitability of the solution space changes, instead of changes in the solution space, it could be due to changes in the manufacturing processes lowering manufacturing costs or changes in choice navigation leading customers to choose products sold at a greater price. Another example is the metric configuration abortion rate which we argue indicates how well the solution space reflects the demand for variety from customers. However, the configuration abortion rate will be strongly influenced by the choice navigation, i.e. how well the configurator is implemented. In future research, metrics for the other two capabilities, Robust Process Design and Choice Navigation should be established and the links between all three capabilities can be analyzed. Furthermore, the relations between metrics performance and specific methods should be addressed so that an assessment could point out not only what a company should do to improve but also how.

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Paper 7

Assessment of Process Robustness for Mass Customization

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Assessment of Process Robustness for Mass Customization

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Abstract. In mass customization, the capability Robust Process Design defined as the ability to reuse or recombine existing organizational and value-chain resources is essential to deliver a high variety cost effectively. We argue that there is a need for methods which can assess a company's process robustness and their capability to develop it. Through literature study and analysis of robust process design characteristics a number of metrics are described which can be used for assessment. The metrics are evaluated and analyzed to be applied as KPI's to help MC companies prioritize efforts in business improvement.

Keywords: Robust Process Design, Mass Customization, Flexibility

1 Introduction

In any company it is essential to offer products which match the needs and desires of customers to achieve sales and profit. This is true for mass producers as well as mass customizers; however in mass customization this issue is somewhat more complex than mass production due to a much higher variety and a more complex product structure. As pointed out by Salvador et al., mass customizers need three fundamental capabilities to be successful: 1) Solution Space Development – Identifying the attributes along which customer needs diverge, 2) Robust Process Design – Reusing or recombining existing organizational and value chain resources to fulfill a stream of differentiated customer needs and 3) Choice Navigation – Supporting customers in identifying their own solutions while minimizing complexity and the burden of choice [3], [7].

In order for companies to be able to establish themselves as mass customizers or for existing mass customizer to improve performance, it is proposed that a set of methods for assessing the three capabilities is developed. In this paper, the focus is solely on the capabilities for Robust Process Design. The research question for this paper is: ***What metrics can be used to assess capabilities for robust process design and how can these be determined?***

The research question is sought answered through first defining robust process design, and in overall terms, what should be assessed. Then a literature review is conducted to identify related metrics already defined in literature. These metrics are evaluated, whether they are descriptive in relation to the robustness of processes, and a final set of metrics is developed. The metrics developed is a preliminary set of metrics, and should be regarded as an assessment framework which will need further validation and refinement in order to be applied in practice.

2 Robust Process Design

The capability robust process design is defined by Salvador et al. [7] as "*Reusing or recombining existing organizational and value chain resources to fulfill a stream of differentiated customer needs*". Hence this capability is related primarily to the capabilities of the manufacturing system, and its ability to manufacture a variety of products. The robustness of the processes, both on a detailed level as well as on enterprise level can be perceived as the ability to adapt to manufacturing a variation of products efficiently, both in terms of time and in terms of cost. However, the robustness of the processes can be interpreted in two different ways:

- The ability to manufacture a variety of products within a fixed solution space, i.e. the current product portfolio / variety – *Robustness towards existing variety*
- The ability to adapt the manufacturing system to accommodate new variety, e.g. when the solution space changes due to new product options - *robustness towards new variety* This has a close relation to solution space development.

Both dimensions of the capability are relevant and critical to MC success; however they are not necessarily correlated. For example would a purely manual production be highly flexible towards new variety compared to a highly specialized and automated production, whereas the latter would probably be more efficient in manufacturing a predefined variety. Hence in order to assess the robustness of processes, we will need to distinguish between these two dimensions.

A study by Wildemann [8] investigated the ratio between product variety and manufacturing unit costs for different manufacturing technologies. This study found that for factories with conventional manufacturing technologies, doubling the variety would imply an increase in unit costs of 20-35%. Flexible automated and segmented plants however would only increase unit costs by 10-15% when doubling the variety. This indicates that there are great differences between the costs of increasing variety. The goal of robust process design is to minimize this ratio, so that increasing variety increases unit costs as little as possible. In the following, the existing literature addressing metrics for process robustness will be reviewed.

3 Literature review

It is generally acknowledged that a late differentiation point or customer decoupling point is an enabler for an efficient MC production. Martin & Ishii [4] defined the Differentiation Point Index (DPI) as a measure of how postponed the variant creation is in a manufacturing process:

$$DPI = \frac{\sum_{i=1}^{n} d_i v_i a_i}{n d_1 v_n \sum_{i=1}^{n} a_i}$$

v_i: #of different exiting in process i
n: number of processes
v_n: final number of varieties offered
d_i: average throughput time from process i to sale
d_1: average throughput time from beginning production to sale
a_i: value added at process i

Similarly the Setup index (SI) was introduced by Martin and Ishii [4] as a measure of how the setup costs contribute to the overall manufacturing costs. The SI metric is defined as:

$$SI = \frac{\sum_{i=1}^{n} v_i c_i}{\sum_{j=i}^{v_n} C_j}$$

v_i: #of different exiting in process i
n: number of processes
v_n: final number of varieties offered
C_j: Total cost of Jth product
c_i: cost of setup at process i

Blecker et al. [1] argue that capacity utilization (CU) is an important metric for mass customization and the definition from Mueller [5] is adopted as:

$$CU = \frac{Processing\ time}{Processing\ time + idle\ time}$$

The CU metric can be calculated for process or aggregated factory level, but in either case, a higher CU would imply a more efficient manufacturing setup implying lower manufacturing costs.
Blecker et al. also defines a production process commonality (PPC) metric, which indicated to what extent manufacturing processes are common to all product variants manufactured. The metric is defined as:

$$PPC = \frac{Number\ of\ common\ production\ processes}{Number\ of\ all\ production\ processes}$$

A delivery time reliability (DTR) metric was further introduced by Blecker et al. [1] . This is relevant as a high DTR will indicate a robust system able to deliver the necessary variety of products. The metric is defined as:

$$DTR = \frac{Agreed\ delivery\ time}{Actual\ delivery\ time}$$

Pine [6] argued that a key metric for Mass Customization production is the work-in process turnover (WIPT), which indicates the value of goods in the manufacturing system compared to sales for a given period:

$$WIPT = \frac{Sales}{Work\ in\ process}$$

Daaboul et al [2] also introduced a number of metrics for mass customization. The Customization Process Indicator (CPI) indicates the relationship between the actual manufacturing time of a customized product and the time a customer is willing to wait for a custom product:

$$CPI = \frac{Total\ time\ for\ customization\ process}{Max\ allowed\ time\ for\ customziation\ process}$$

The metric Quality of Order Reception (QOR) indicates how well the production performs in terms of on time delivery and the defect rate [2]:

$$QOR = \frac{\#\ of\ orders\ delivered\ on\ time\ \cap \#\ of\ orders\ with\ zero\ defects}{total\ \#\ of\ orders}$$

Finally the Order Delay Time (ODT) indicates how fast a manufacturer is able to deliver a customized product:

$$ODT = Time\ elapsed\ between\ order\ placement\ and\ order\ reception$$

The metrics defined in literature to some extent all support the assessment of process robustness, however in different ways, and not necessarily towards both existing variety and new variety. In the following section, it will be evaluated which metrics can support the assessment of process robustness.

4 Metrics for Process Robustness Assessment

4.1 Robustness towards existing variety

Two of the metrics found in literature are related to standardization of the manufacturing processes; those are differentiation Point Index (DPI) and production process commonality (PPC). PPC gives an indication of to what extent manufacturing processes for different processes are common and DPI indicates the postponement of variants and on the other hand how many manufacturing processes have to change due to product variety. The most postponed manufacturing setup is expected to support highly robust manufacturing processes and therefore a very good indicator of robust process design. Because of that the DPI metric is chosen.

The Setup Index (SI) addresses the cost of setup of manufacturing processes compared to the total cost of a product. Since a high setup cost would be an indicator of a low robustness, this indicator can contribute to the assessment of process robustness.

In the literature review, three different metrics were identified which are related to time performance of the manufacturing system, i.e. the delivery time reliability

(DTR), Quality of Order Reception (QOR) and the Order Delay Time (ODT), Customization Process Indicator (CPI). Although these metrics are not direct indicators of process robustness, it is expected that highly robust manufacturing processes will have a good time performance and good performance within these metrics will indicate robust processes. The metrics QOR and DTR however are very similar, and it is thus chosen only to include the QOR metric since it not only takes into account delivery performance but also quality of the product.

The metrics Capacity Utilization (CU) and work-in process turnover (WIPT) are considered important metrics which can indicate the state of a manufacturing system; however they are not considered essential in relation to assessing process robustness and are thus not included in the final set of metrics.

In addition to the metrics identified in literature we propose two additional metrics for process robustness which are defined below:

The metric Number of different modules manufactured per process (NMP) gives a measure of the average number of modules manufactured in the different manufacturing processes:

$$NMP = \frac{\sum_{i=1}^{n} m_i}{n} \quad m_i\text{: \# of different modules manufactured at process i} \quad n\text{: : \# of different processes}$$

A higher NMP will indicate robust processes, since each process will be able to manufacture more different modules and thus a higher number of end variants.

The metric Degree of manual labor (DML) can be used as an indirect indicator of process robustness, since a low need for manual processing will indicate that the non-manual manufacturing processes are able to supply a high variety. The DML metric is defined as:

$$DML = \frac{\sum_{i=1}^{n} \frac{lc_i}{tc_i}}{n} \quad lc_i\text{: labour cost for manucaturing product i} \quad tc_i\text{: total cost of manufacturing product i} \quad n\text{: \#of different products}$$

4.2 Robustness towards new variety

Only the SI metrics found in the literature were considered good measures of process robustness towards new variety and is chosen as metrics which could be useful in assessment of robust process design. This metric however is not considered sufficient for assessing the robustness towards introduction of new variety and hence four additional metrics are proposed:

Process variety increase (PVI) indicates how much the variety of manufacturing processes increases when a new product option or product is introduced in the manufacturing system. The PVI metric, calculated as an average during a period in time, is defined as:

$$PVI = \frac{\sum_{i=1}^{n} p_i}{n} \quad \mathrm{p}_i\text{: \# of new processes introduced for product option i} \quad \text{n: \#of new product options in the period}$$

A low PVI will indicate a high robustness since this implies that few new processes need to be introduced when a product option is introduced and thus that the existing processes can accommodate new product variety.

In addition to the PVI metric the Capacity expense (CAPEX) increase when introducing a new option (CAPIV) is introduced. This is done since a high PVI does not necessarily come a high cost, given a new process is implemented on existing flexible equipment. The CAPIV metric, also calculated as an average over a period of time, is defined as:

$$CAPVI = \frac{\sum_{i=1}^{n} capi_i}{n}$$

$capi_i$: Percentual CAPEX increase from introducing product option i
n: #of new product options in the period

The time and cost to introduce new product variety are also important metrics to assess process robustness, since robust processes will imply low cost and fast introduction of new product variety. The metrics Time to introduce a new option in the manufacturing system (TIV) and Cost of introducing a new option in the manufacturing system (CIV) are thus defined as:

$$TIV = \frac{\sum_{i=1}^{n} ti_i}{n}$$

ti_i: time from product design finish to manufacturing system ready
n: #of new product options in the period

$$CIV = \frac{\sum_{i=1}^{n} ci_i}{n}$$

ci_i: cost of introducing product option i
n: #of new product options in the period

5 Conclusion

In order to support the development of production in mass customization, metrics are needed in order to assess the robustness of processes. To establish these metrics, relevant literature was reviewed and several applicable metrics were identified. Further metrics were defined in areas where no sufficient metrics could be identified in literature. The following list compiles the metrics identified in literature and newly defined metrics within the two areas robustness towards existing variety and robustness towards new variety:

Metrics identified in the literature

- Differentiation Point Index (DPI)
- Setup Index is the cost of setup of manufacturing processes (SI)
- Quality of Order Reception (QOR)
- Number of different modules manufactured per process (NMP)

Newly defined metrics

- Number of different modules manufactured per process (NMP)
- Degree of manual labour (DML)
- Percentage point increase in process variety (PVI)
- Capacity expense increase when introducing a new option (CAPIV)
- Time to introduce a new option in the manufacturing system (TIV)
- Cost of introducing a new option in the manufacturing system (CIV)

The reason why new metrics were introduced is that the metrics identified in literature were found insufficient for a number of purposes. In relation to process robustness towards existing variety, the metrics NMP and DML were introduced because the existing metrics focused on the robustness of a manufacturing system as a whole. The new metrics seek to assess the robustness on individual process level. The four new metrics PVI, CAPIV, TIV and CIV were introduced simply because no existing metrics were found in literature supporting the assessment of process robustness towards new variety.

It is the intention that these metrics can be used to in MC companies for different purposes. One purpose is benchmarking against "best practice" mass customizers, in order to identify areas with the greatest potential for improvement. Another purpose is to use these metrics as key performance indicators which are continually calculated to monitor performance to continuously improve. In relation to research in mass customization it is the intention to apply these metrics in different types of mass customization companies to analyze what distinguishes successful mass customizers.

It is evident that the application of these metrics poses certain requirements related to data availability and quality. However, most MC companies already have systems in place which are very likely to contain the data required for calculating the metrics presented in this paper.

As mentioned in the introduction, robust process design is one of three fundamental capabilities for successful mass customizers; the other two solution space development and choice navigation. There are strong relations between these three capabilities, and phenomena experienced in a company cannot necessarily be attributed to only one capability, and as such, the metrics defined in this paper can also be influenced by other factors than the robust process design capability.

When research of identifying existing metrics with further literature review and defining metrics for all three capabilities has been finalized, the future research should establish the links between all three capabilities. Furthermore, the relations between metrics performance and specific methods should be addressed so that an assessment could point out not only what a company should do to improve but also how.

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Paper 8

Choice Navigation Assessment for Mass Customization

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Choice Navigation Assessment for Mass Customization

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Abstract

In mass customization, the capability Choice Navigation which is defined as the ability to support customers in identifying their own solutions while minimizing the burden of choice, is essential to market high variety product portfolios effectively. We argue that there is a need for methods which can assess a company's choice navigation and their capability to develop it. Through literature study and analysis of choice navigation characteristics a number of metrics are described which can be used for assessment. The metrics are evaluated and analyzed to be applied as KPI's to help MC companies prioritize efforts in business improvement.

1 Introduction

In any company it is essential to offer products which match the needs and desires of customers in order to achieve sales and profit. This is the case for mass producers as well as mass customizers; however in mass customization this issue is somewhat more complex than mass production due to a much higher variety and a more complex product structure. As pointed out by Salvador et al., mass customizers need three fundamental capabilities to be successful (figure 1): 1) Solution Space Development – Identifying the attributes along which customer needs diverge, 2) Robust Process Design – Reusing or recombining existing organizational and value chain resources to fulfill a stream of differentiated customer needs and 3) Choice Navigation – Supporting customers in identifying their own solutions while minimizing complexity and the burden of choice [Lyons et al., 2012; Salvador et al., 2009].

In order for companies to be able to establish themselves as mass customizers or for existing mass customizers to improve performance, it is proposed that a set of methods for assessing the three capabilities is developed. In this paper, the focus is solely on the capabilities for Choice Navigation. The research question for this paper is:

What metrics can be used to assess capabilities for choice navigation and how can these be determined?

The research question is addressed by first defining choice navigation, and in overall terms, which areas should be assessed. Then a literature review is conducted to identify existing metrics. These metrics are evaluated in order to evaluate whetherthey are can be applied to assess the choice navigation performance, and a final set of metrics is developed including newly defined metrics.

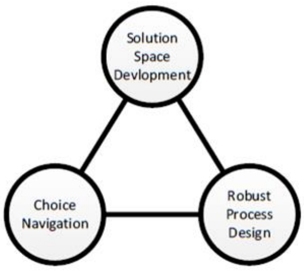

Figure 1 The three fundamental capabilities in mass customization [Salvador et al., 2009]

2 Choice navigation

The capability choice navigation is defined by Salvador et al. [Salvador et al., 2009] as "Support customers in identifying their own solutions while minimizing complexity and the burden of choice". Hence this capability is related primarily to the capabilities of the configuration system, and its ability to configure a variety of products.

Salvador et al. proposes three different approaches to develop the capabilities within choice navigation: Assortment Matching, Fast-cycle, trial-and-error learning and Embedded configuration. However these support the development of choice navigation rather than the assessment of choice navigation capabilities.

Two different perspectives are relevant when assessing a company's choice navigation capabilities. The first perspective addresses the capabilities for supporting the customer in choosing a product which matches the customer's needsfulling. The second perspective is concerned with how well the choice navigation supports the business process involved in product configuration. This paper will focus on the assessment of choice navigation purely from the customer's perspective, thus focusing on the capabilities supporting the customer in the configuration process.

The ideal product configurator should after a customer has finished a configuration leave the customer with the experience that the process has not been unnecessarily difficult to perform and the customer has been able to match his or her needs exactly to a specific configuration of a product [Salvador et al., 2009].

Supporting the customer in the configuration process, thereby making the product configuration task easy and fast, is a matter of aiding the customer in matching characteristics of needs, empowering customers in building models of needs or embedding the configuration in the product itself [Salvador et al., 2009]. Measuring how well choice navigation in a specific company ensures a 100% fit between customer needs and the goods configured by the customers is a somewhat difficult task.

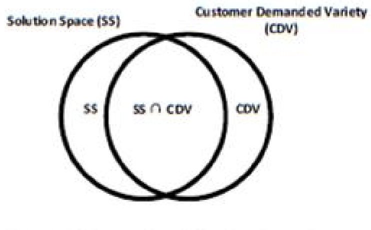

Figure 2 The intersection of offered variety and customer demanded variety yields the potential sellable products.

The problem of assessing the fit between customer needs and a configured product can be described using set theory. Since the objective of choice navigation is to match the customer demand with the offered solution space, a set is defined for each of these as illustrated in figure 2. The optimality of a solution space can then be described by defining two sets of products: 1) the different products offered by an MC company, defined as the set SS (Solution Space) and 2) the variety of products which are demanded by the customers, defined as the set CDV (Customer demanded variety). As illustrated in figure 1, the intersection of the two sets will represent the products offered by the MC company which correspond to products demanded by customers. The intersection of the two sets thus represents the products that customers may buy, given they are able to find and configure the products and willing to pay the required sales price.

Intuitively, maximizing the set $SS \cap CDV$ would seem like a good idea since this would maximize the potential number of product variants that can be sold to customers. It would also seem intuitive that the set $SS \setminus CDV$ i.e. products which are part of the offered variety but are not demanded by customers should be minimized or even eliminated.

When describing these sets, it should be defined which elements are in the set or in other words. What is an element? One possibility would be that each element in the sets corresponds to a unique product variant. Following this, each possible combination of configuration choices would correspond to a variant and thus an element in the set. However, for most MC product families, the number of elements becomes astronomical due to numerous configuration variables each with a number of outcomes. For example, when configuring a Mini Cooper online the configuration choices presented to the customer will result in a number of possible variants well above a 20 digit figure. This is obviously significantly more than the potential market of the Mini Cooper. Assuming that the sale of Mini Coopers is a good representation of the demanded variety, and the Mini Cooper has sold a few million cars and assuming that each sold Mini Cooper is unique, the customer demanded variety will only be a tiny fraction of the offered variety and as a consequence. Furthermore we would expect that assessing whether single variants would counter a demand from a customer is simply not possible if the number of variants is high. Thus it would seem that variants defined as all possible combinations of configuration variables is not an appropriate way to define the solution space set as well as assessing the intersection of SS and CDV.

A more simple and comprehensible way of representing the sets may be defining the elements of the sets as the "dimensions of customization". If a product has a number of customizable attributes and each attribute has a finite number of values that can be chosen, each value will correspond to a product property which can potentially be demanded by a customer.

We thus propose that the solution space is described by the number of customizable attribute's values. For example if a product can be configured in two different sizes and ten different colors, the SS set will contain 12 elements; two size elements and ten color elements. Defining the solution space this way is trivial, since an MC company's offerings will usually be explicit in a configurator, product family model or other documentation. Defining the set CDV on the other hand is far more difficult since it will be impossible or at least extremely time consuming to clarify all potential customers' demand for variety. Also this would depend on the delimitation of the product family's intended customer base. As a result, measuring the size of CDV will expectedly be practically impossible. The intersection of SS and CDV however only describes which products match the demand of customers, and not whether the customers actually buy the products. Whether the customers buy the products is a matter of several other factors; however the first obstacle is whether the customers are able to match the needs with an actual product configuration, which is the essence of choice navigation. For this reason, we introduce another set, Customer Configuration (CC), which contains the variety that is actually being configured by customers.

The Set CC intersects with both SS and CDV as shown in figure 2, and intuitively the intersection of all three sets SS∩CDV∩CC indicates the optimal situation, where the solution space satisfies a customer demand and the customer is able to configure the product. Conversely, all variety not contained in SS∩CDV∩CC could indicate a problem.

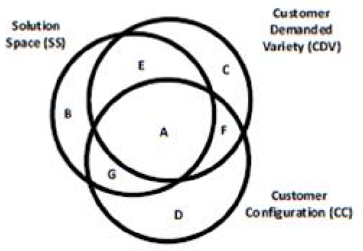

Figure 3 Intersection of Solution Space, Customer Demanded Variety and Customer Configuration

Analyzing figure 3, intersections B and C are consequences of a mismatch between the actual demand and solution space, where B implies variety which is part of the solution space but has no demand thus potentially implying unnecessary complexity costs. C implies a demand for variety that is not met by the current solution space and which may indicate an intersection where the development of the solution space could increase sales. The D intersection is seemingly less interesting in terms of choice navigation, since they relate primarily to the capabilities within solution space development.

In intersection D the customer configures a product that does not meet the demand nor is it contained in the solution space. This is not a typical situation but is nevertheless undesirable, and would likely be indicated by the customer abandoning the configuration. In intersection E, there is a match between the variety offered by the company and the customer demand; however the customer does not configure the product. This is likely a result of a user interface unable to guide the customer satisfactory through the configuration process. Intersection F indicates configuration which match a customer demand, but is outside the actual solution space, i.e. a product that can be configured but not produced, which is also highly undesirable. Finally, in intersection G the customer configures a product that is within the solution space but does not meet the demand thus resulting in a customer disappointment.

The description of the sets CC, CDV and SS above will be used in the following as criteria for evaluating and developing different metrics used for assessing choice navigation capabilities, since metrics indicating variety outside SS∩CDV∩CC will indicate sub optimality within choice navigation.

When assessing a companys capabilities within choice navigation it must be considered within which kind of business environment the configuration will be done. There is typically a great difference in choice navigation setups depending on whether the sales process is done in a business to business (B2B) or in a business to consumer (B2C) sales process. Both setups can be assessed using the same choice navigation metrics, however there are typically differences in the sales setups, where in B2B it is often the sales organization performing the actual configuration process, whereas in B2C this is typically performed by the end customers. Due to this difference, assessessment metrics for choice navigation should be investigated for bias or benchmarking issues when using the results across the different business environments B2B and B2C. We will in this paper not these differences further.

Choice Navigation metrics representing time and effort to reach a configuration, should ideally be developed so that all assessment results could be benchmarked against each other. However regocnising differences between different products and business setups, the metrics should at least allow for benchmarking within a product type and business environment.

One example where differences in product types could make benchmarking between different products non representative is where customers have a great interest in the product and actually wish to spend long time on the configuration process making it more than an experience than a transaction. In this case, a metric indicating high performance for shorter configuration processes might not be representative for the goal the configurator is designed to achieve. Hence, each metric should be scrutinized in relation to assessing a specific product, as special considerations might be relevant for special products.

3 Literature review

Blecker et al. identified and developed a number of metrics for varity steering [Blecker et al., 2003]. Some these metrics are relevant for assessment of choice navigation, and these are identified in the following along with other relevant metrics from literature.

Average configuration length of time metric (CT)

$$CT = \frac{\sum_{i=1}^{N} CT_i}{N} \quad (1)$$

CT: *average configuration lenght of time*
CT_i: *time needed for customer to fulfil one configuration*
N: *number of configurations*

source: [Blecker et al., 2003]

This metric measures how long time a customer or sales person uses for performning the acutal configuration process

Configuration abortion rate metric (CA)

$$CA = \frac{N_a}{N_p} \quad (2)$$

CA: configuration abortion rate metric
N_a: number of aborted configuration processes
N_p: number of logins (started configurations)

source: [Blecker et al., 2003]

The CA metric describes how frequently customers or sales people choose to abort a configuraiton which has been initiated due to whatever reason.

Customers Return Rate metric (RTR)

$$RTR = \frac{\text{number og returned products}}{\text{number of delivered products}} \quad (3)$$

source: [Piller, 2002]

The RTR metric describes how often customers returns a product to the company after receiving it due to e.g. disappointment in the product.

Customers Churn Rate metric (CR)

$$CR(\Delta T) = \frac{NOLC(\Delta T)}{NOC(\Delta T) + NONC(\Delta T) - NOLC(\Delta T)} \quad (4)$$

NOLC: number of lost customers at ΔT
NOC: number of customers at T
NONC: number of new customers at ΔT

source: [Sterne, 2003]

The CR metric describes the relationship between new customers and lost customers.

Customers Repurchase Rate metric (RR)

$$RR = \frac{\text{repurchase through existing customers } (\Delta T)}{\text{number of new customers } (\Delta T)} \quad (5)$$

source: [Piller, 2002]

The RR metric describes how often products are repurchased, or how often customers return to byt another different product.

Customers Complaints Rate metric (COR)

$$COR = \frac{\text{number of complaints } (\Delta T)}{\text{number of deliveries } (\Delta T)} \quad (6)$$

source: [Blecker et al., 2003]

Similar to the CR metric, the COR metric describes how often customers complain over a product they have purchased after receiving it.

Walcher and Piller conducted a survey of 500 different mass customization companies, and for this purpose they developed a number of metrics for comparing the different mass customizers [Walcher & Piller, 2012]. The analysis focused primarily on the configurators, i.e. choice navigation but also on the products. Four objective metrics were included:

- Visual features – To what extent the product is visualized as it is configured, e.g. 2D picture, multuple views, Zoom etc.
- Navigation help – Whether help like progress bars, activity lists, option to save etc. is provided
- Company help – Whether help like recommendations, deeper explanations, design examples etc. is present
- Customer help – Whether users of the configurator is able to get help or inspiration from other users directly or indirectly.

The metrics were evaluated on a scale from 0-4 representing how many of the elements were found in each configurator.

Furthermore, evaluators which were independent mass customization experts were asked to evaluate each configurator using the following subjective metrics:

- Visual realism
- Usability
- Creativity
- Enjoyment
- Uniqueness
- Choice options

Each metric consisted of a number of sub-metrics which the evaluators were asked to assign a rating between 1 and 5. Each configurator was evaluated by 3 different experts and an average was calculated for each metric for each configurator.

4 Choice navigation metrics

In order to evaluate which metrics are usable for evaluating choice navigation capabilities, the different set intersections illustrated in figure 2 are addressed individually. For each intersection, it is evaluated which metrics can support the assessment.

Another requirement for the metrics is that they should be measurable based on readily available data in a company's IT systems, i.e. ERP, CRM, PLM and configuration systems, since this would allow mass customizers to utilize these metrics for continous improvement.

Please note that intersections B and C are disregarded in this context since they relate more to capabilities within solution space development than choice navigation.

4.1 Intersection E

In this case, the customer will start to configure a product, but never reach a final configuration which is purchased, although the solution space supports the requirements. This is difficult to distinguish from the case where requirements cannot be met within the existing solution space (intersection C), however high CA metric can be used as an indication since customers that cannot configure a product to meet their requirements will likely abandon the configuration.

Furthermore, if configurations utilise only a small portion of the solution space and if many configuration variables, rarely deviate from the default values, that may indicate that customers are not aware of all possible variety and have therefore not been able to configure a suitable product although it is in fact offered.

4.2 Intersection F

In this case, customers configure products which are within the customer demanded variety but outside the solution space, i.e. a product is configured which cannot be delivered. This would likely result in the order being cancelled by the company, since it cannot be manufactured. Alternatively, the company will change the configuration to fit within the solution space by e.g. upgrading the product. As an indicator for these configurations we introduce two new metrics:

Seller Order Cancellation rate (SOCR)

$$SOCR = \frac{number\ of\ orders\ cancelled\ by\ seller}{number\ of\ placed\ orders} \quad (7)$$

Seller Order change rate after purchase (SOCRAP)

$$SOCRAP = \frac{number\ of\ orders\ changed\ by\ seller}{number\ of\ placed\ orders} \quad (8)$$

High values of SOCR and SOCRAP would then indicate configurations within intersection F.

Configurations within intersection F as well as D would be a result of a faulty implementation of a configurator, since a configurator should ideally reflect the company's solution space or a subset of the solution space. Reaching configurations within intersection F and D is very undesirable, since it will lead to loss of credibility as well as a need for costly manual business processes to resolve the issue.

4.3 Intersection G

In this case, the customer configures a product which is within solution space but does not correspond to the customer's requirements. In this case several things could happen. If the customer realises that the product is not satisfactory prior to delivery, the customer may cancel the order or change the configuration. To indicate this, two new metrics are introduced:

Customer Order Cancellation rate (COCR)

$$COCR = \frac{number\ of\ orders\ cancelled\ by\ customer}{number\ of\ placed\ orders} (9)$$

Customer Order change rate after purchase (COCRAP)

$$COCRAP = \frac{no.of\ orders\ changed\ by\ customer}{number\ of\ placed\ orders} (10)$$

In other cases, customers will not realise that the configured product does not meet requirements, until it is received. In this case the customer may return the product (indicated by RTR) or complain (indicated by COR). Also repurchase rates (RR) and churn rates (CR) would be affected.

Hence configurations within intersection G would be indicated by high values of COCR, COCRAP, RTR and COR and CR and low values of RR.

4.4 Intersection D

In this intersection, the customer configures a product with properties that the customer does not have a demand for and is not part of the solution space. In this case either the customer or the company can react to this and either cancel or change the order. Hence configurations in intersection D will be indicated by High values of SOCR, SOCRAP, COCR and COCRAP. It may however be difficult to determine whether high values of SOCR and SOCRAP are due to configurations in intersection D or F. On the other hand, the customer does not receive the product no matter which are the configuration is in, so whether the customer had a demand for the product may be less important.

4.5 Intersection A

Basically, sales within intersection A are the optimal solution, since products are sold within the solution space which also match the customers' requirements. Hence if there is little indication of configurations outside intersection A, then that should indicate that configurations are within intersection A. Since configurations within intersection A should lead to a sale, then an increase in CSR would also indicate an increase in configurations within intersection A.

Configuration sales rate metric(CSR)

$$CSR = \frac{number\ of\ sold\ configurations}{number\ of\ started\ configurations} \quad (11)$$

4.6 Further metrics

Apart from the metrics which relate directly to the intersections A-G, we identified a number of metrics which may be used to explain why configurations occur in intersections outside intersection A. Hence the metrics can be used to explain the possible reasons for a problem with a configuration system rather than whether there is in fact a problem.

Configuration click index metrics(CI)

$$\mathrm{CI}_c = \frac{\sum_1^n C}{V} \quad (12)$$

CI_c: *clicks index of configuration*
n: *number of configuration in index (min 100)*
C: *number of clicks used for configuration i*
V: *numbers of outcome of variables*

CI metric is a measure of the number of selections, choices or clicks the customer makes in the configurator; or in other words the effort needed by the customer for performing the configuration. It could be the number of selections or actions which the customer has made for a number of given configurations indexed with the total number of variables available in the configurator. The metric cannot be used as benchmark in general or as comparison to other companies/configurators but it can be used internally as an indicator for how a change due to implementation of new variables in the configurator or change of configurator has impacted the choice navigation performance. Increase of CI may indicate more complex choice navigation or an increase in burden of choice navigation. In a broad view it can be argued that a a value of CI at or near one may indicate a perfect choice navigation.

Time used in configuration index metric(TI)

$$\mathrm{TI}_c = \frac{\sum_1^n T}{V} \quad (13)$$

TI_c: *configuration time index*
n: *numberof configuration in index* $(min\,100)$
T: *time in seconds used for configuration*
V: *numbers of outcome of variables*

As for CI the TI metrics gives an index of the time used for a number of given configurations. As for CI the TI may be used internally as an indication of change in burden of choice caused by change of variables and/or change of configurator.

Some of the metrics defined in MC500[Walcher & Piller, 2011] can also be utilized as metrics in this context. However only the objective metrics are included here, and thereby not the metrics that are based on a subjective evaluation. The included metrics are:

- Visual features
- Navigation help
- Company help
- Customer help

All of these metrics are indicators of how customers are guided or helped through the configuration process. Given a company finds that many configurations are observed in intersections E or G, then looking into these metrics may explain the reasons for this.

5 Conclusion & Dicsussion

In order to support the development of choice navigation in mass customization and thereby also product configuration, metrics are needed in order to assess the choice navigation performance. To establish these metrics, relevant literature was reviewed and several applicable metrics were identified. Further metrics were defined in areas where no sufficient metrics could be identified in literature. The following list compiles the metrics identified in literature and newly defined metrics within choice navigation:

Metrics identified in the literature

- Configuration abortion rate metric (CA)
- Customers Return Rate metric (RTR)
- Customers Churn Rate metric (CR)
- Customers Repurchase Rate metric (RR)
- Customers Complaints Rate metric (COR)

Newly defined metrics

- Seller Order Cancellation rate (SOCR)
- Seller Order change rate after purchase (SOCRAP)
- Customer Order Cancellation rate (COCR)
- Customer Order change rate after purchase (COCRAP)
- Configuration sales rate metric(CSR)

It is the intention that these metrics can be used in MC companies for different purposes. One purpose is benchmarking against "best practice" mass customizers, in order to identify areas with the greatest potential for improvement. Another purpose is to use these metrics as key performance indicators which are continually calculated to monitor performance to continuously improve. In relation to research in mass customization it is the intention to apply these metrics in different types of mass customization companies to analyze what distinguishes successful mass customizers.

It is evident that the application of these metrics poses certain requirements related to data availability and quality. However, most MC companies already have systems in place which are very likely to contain the data required for calculating the metrics presented in this paper.

As mentioned in the introduction, choice navigation is one of three fundamental capabilities for successful mass customizers; the other two being robust process design and solution space development. There are strong relations between these three capabilities, and phenomena experienced in a company cannot necessarily be attributed to only one capability, and as such, the metrics defined in this paper can also be influenced by other factors than the solution space development capability.

One example is the metric configuration abortion rate which we argue indicates how well choice navigation is implemented. However, the configuration abortion rate will be strongly influenced by the solution space, i.e. how well the offered variety matches the demanded variety. The value of this metric can thus both be influenced by a company's performance within choice navigation as well as solution space development. In future research, metrics for the other two capabilities, Robust Process Design and Solution Space Development should be established and the links between all three capabilities can be analyzed. Furthermore, the relations between metrics performance and specific methods should be addressed so that an assessment could point out not only what a company should do to improve but also how.

When performing an assessment and interpreting the values of the metrics, the interpretation should take into account the product type. Also when benchmarking, different products cannot necessarily be compared directly. The reason for this is that several metrics are based on the customers actions, and these actions will depend on the product type. For exampe if a customer buys a customized car compared to a customized bag of muesli, then the customer would probably be more likely to complain or return the car if it has a wrong color compared to the muesli, if a wrong ingredient has been added. In that case, the difference would be due to the dfference in cost of the products. Furthermore a metric like the repurchase rate makes more sense for some product types than others. For example, customers are likely to repurchase muesli more often than cars. So this metric would depend on to what extent a product can be characterised as a consumable or a durable, and in case it is a durable, how long the life cycle is.

With this paper we have ended a preliminary research of assessment and measurement of the mass customization process. We have with this paper finalized a general approach describing how to assess and measure mass customizatioin and developed a framework of potential metrics useful for assessment and measurement of mass customization, whether this is for the purpose of internal performance indicators or it is used for benchmarking in general. Next phase in this research will be test and evaluation of the metrics.

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Paper 9

Mass Customisation Assessment and Measurement Framework

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Mass Customisation Assessment and Measurement Framework.

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Abstract

Mass customisation involves three fundamental capabilities: Robust Process Design, Choice Navigation and Solution Space Development. A Survey has indicated that a number of companies have ceased mass customizing less than one year after initiating the effort. One reason for this is poor knowledge about the mass customisation progress and guidance of continuous improvement. This paper will conceptualize a framework for measurement and assessment of a company's mass customisation performance, utilizing metrics within the three fundamental capabilities. By assessing performance companies can identify within which areas improvement would increase competitiveness the most and ultimately enabling more efficient transition to mass customisation.

Keywords:

Mass Customisation, Assessment, Metrics, Capabilities

1 INTRODUCTION

To address the increasing customer demand for individually customized products, mass customisation has been widely adopted as a competitive business strategy during the last two decades [1-4]. Many companies have experienced that the implementation of MC is much more complicated than immediately anticipated and in some cases even jeopardized the existence of the company instead of increasing competitiveness. Meanwhile others like DELL, BMW, and ADIDAS have shown that success is indeed feasible [4].

The reason why shifting to mass customisation is so difficult is that it is fundamentally different from mass production. In product development, families of products must be developed instead of individual products. In the sales process, vast amounts of information must be exchanged between customer and company to configure the right product and allow the company to manufacture it. In manufacturing, products are manufactured in batches of one as opposed to mass production where batches are hundreds or thousands of identical products. This basically renders a mass production system useless in relation to mass customisation manufacturing. In relation to logistics, a specific product must be moved from the manufacturing facility to the end customer, whereas in mass production a number of products are shipped from the manufacturer to a warehouse to a retailer where it is sold to the end customer. This further introduces a challenge since mass customisation products cannot be stocked and can only be produced once a customer order is given. All the challenges described above need to be addressed if a company wishes to pursue an mass customisation strategy, which in many cases has proven more difficult than anticipated.

Due to the large difference in success for companies implementing mass customisation, analyses and method development has been addressed extensively in literature [5,6],[7]. Much research has focused on identifying the different enablers for achieving mass customisation and Silveira et al. [6] and Fogliatto [7] present an overview of the research into mass customisation enablers, which is by Fogliatto et al. [7] divided into the categories: 1) Methodologies, 2) design processes, 3) manufacturing processes, 4) supply chain coordination, 5) manufacturing technologies and 6) information technologies.

As pointed out above, manufacturing system flexibility is essential in mass customisation. It has also been generally acknowledged that a reconfigurable manufacturing system is an important enabler for mass customisation [8]. A reconfigurable manufacturing system is according to Koren et al. (1999) [9] a manufacturing system with adjustable structure allowing for scalability according to market demand as well as adaptability to new products. Since the aim of reconfigurable manufacturing system is to possess the capacity and flexibility needed when required [10], this manufacturing system type is highly relevant in relation to mass customisation [11]. Since mass customisation markets are typically dynamic and a continuous development of the solution space for products must be developed over time [4], the need for reconfigurable manufacturing systems compared to flexible manufacturing systems is further emphasized.

1.1 Mass customisation capabilities

Recent research has shown that the ability to transform a business into a successful mass customisation business depends primarily

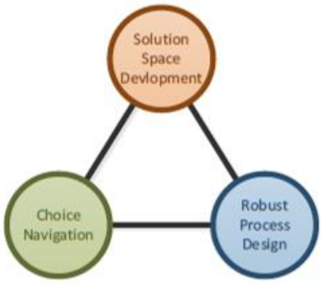

Figure 1: Mass customisation three fundamental capabilities [1].

on three fundamental capabilities [4,12] (Figure 1): 1) Robust Process Design – *Reusing or recombining existing organizational and value chain resources to fulfil a stream of differentiated customer needs*, 2) Solution Space Development – *Identifying the attributes along which customer needs diverge* and 3) Choice Navigation – *Supporting customers in identifying their own solutions while minimizing complexity and the burden of choice*. Robust process design, as termed in that research, is obviously closely linked to reconfigurable manufacturing systems. Robust process design is somewhat broader defined than only the manufacturing processes, since robust process design also involves business processes and logistics processes.

A company mastering each of the three capabilities will thus have increased chances of succeeding as a mass customizer [4]. Hence, in order to successfully implement mass customisation, companies must not only be capable of robust process design and thus the development of reconfigurable manufacturing system, but also the two other capabilities.

Although these three capabilities are identified and described theoretically in literature, mass customisation firms are still faced with a challenge when evaluating their capabilities to identify where performance lacks since no integrated method is available serving this purpose.

The objective of this research is to identify the relations between mass customisation tools and methods, mass customisation capabilities, the sales and operations in a company and ultimately the profitability and thereby competitiveness of the company. Furthermore the aim is, by identifying these relations, to be able to measure a company's performance within each capability and thereby indicating which tools and methods should be applied with the greatest improvement as a result.

1.2 Mass customisation performance measurement

Performance measurement has long been applied as a tool for improving performance, and since tools like the balanced scorecard have emerged, focus within performance measurement has to some extent shifted from purely financial measures to non-financial measures [13]. Many publications indicate that performance measurement does in fact improve performance; the evidence has been much discussed in literature [14]. It has proven a tremendous tool for assisting in improving performance, performance measurement itself cannot guarantee performance improvement, since the effect of performance measurement depends on a number of factors [14]. Bourne et al. (2005)[14] analysed these factors and organized them into three groups: 1) context 2) content and 3) process. The context factors include the companies' external environment as well as internal factors such as structure, culture, strategy and resources [14]. The content factors are related what the performance measurement system actually measures, i.e. the definition of measures, dimensions and structure of the measures [14]. Finally the factors related to the process address the process in which the measures are 1) designed, 2) implemented, 3) used and 4) refreshed.

Hence a high number of different factors determine whether a performance measurement system has a positive effect on performance, both factors which can be influenced during the development of a performance management system, but also the contextual factors.

Relating this to a mass customisation context, a performance measurement system for mass customisation should be designed with these different factors in mind, but it also implies that one single performance measurement system will not fit all mass customisation companies, since these companies will have different contexts. However, literature generally agrees that performance measurement systems should be aligned with the companies' strategies [13].

In order to develop the three fundamental mass customisation capabilities described by Salvador et al. [4], performance measurement is considered an important enabler, however the performance measurement system must be developed specifically to fit mass customisation and for a specific mass customisation company to be effective. In this research we look into the specific content, rather than context and process of performance management systems to address the three fundamental capabilities.

In the research presented in this paper we identified the metrics needed to develop a performance measurement system for mass customisation, assuming this will be a valuable tool for companies to be able to establish themselves as mass customizers or for existing mass customizers to improve performance. The research question is:

What metrics can be used to measure performance and thereby assess capabilities for choice navigation, solution space development and robust process design and how can these be determined?

The research question has been answered through first defining each capability, and in overall terms, what should be assessed. Then a literature review is conducted to identify related metrics already defined in literature. These metrics are evaluated, whether they are descriptive in relation to the choice navigation, and a final set of metrics is developed for each capability. In previous papers, thorough literature reviews have been conducted and metrics defined in greater detail [15-18]

2 METRICS

The metrics for assessing a company's mass customisation progress as well as their development of capabilities need to reflect the process. Furthermore metrics need to be measurable; otherwise they are per definition not metrics. This means that for each metric, the required data should preferably be readily available in the company or should be easily obtainable. Luckily, most mass customisation companies have information systems which could support this, such as configurators, Product Lifecycle Management (PLM) systems, Enterprise Resource Planning (ERP) systems, Engineering Change Management (ECM) systems etc., which we expect would provide most of the required data.

2.1 Choice navigation metrics

The choice navigation capability is related primarily to the capabilities of the configuration system, and its ability to configure a variety of products. The customer experience from a product configuration process should aim for a result where the customers recognize that the configuration process supports the customer's requirements and offers the products which fulfil the customer's exact needs [4].

Supporting the customer in the process, making the product configuration easy and fast, is a matter of making it easy to match characteristics of needs, empower customer in building models of needs or embed the configuration in the product [4], from an assessment point-of-view this is potentially measurable. Measuring how well the choice navigation ensures a 100% fit between customer needs and the goods configured by the customers however seems more difficult. Using set theory we have defined and introduced sets to identify areas of interest and potential measurable areas. For assessment of choice navigation 3 sets have been defined and 6 areas of interest have been identified (Figure 2)

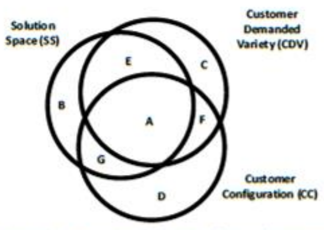

Figure 2: Intersection of Solution Space, Customer Demanded Variety and Customer Configuration [18].

Analysing Figure 2, intersections B and C are consequences of a mismatch between the actual demand and solution space, where B implies variety which is part of the solution space but has no demand thus potentially implying unnecessary complexity costs. C implies a demand for variety that is not met by the current solution space and which may indicate an intersection where the development of the solution space could increase sales. The D intersection is seemingly less interesting in terms of choice navigation, since they relate primarily to the capabilities within solution space development.

In intersection D the customer configures a product that does not meet the demand nor is it contained in the solution space. This is not a typical situation but is nevertheless undesirable, and would likely be indicated by the customer abandoning the configuration. In intersection E, there is a match between the variety offered by the company and the customer demand; however the customer does not configure the product. This is likely a result of a user interface unable to guide the customer satisfactory through the configuration process. Intersection F indicates configuration which match a customer demand, but is outside the actual solution space, i.e. a product that can be configured but not produced. Finally, in intersection G the customer configures a product that is within the solution space but does not meet the demand thus resulting in a customer disappointment.

The description of the sets CC, CDV and SS above has been used as criteria for evaluating and developing different metrics used for assessing choice navigation capabilities, since metrics indicating variety outside SS∩CDV∩CC (Area A) will indicate sub optimality.

In order to evaluate which metrics are usable for evaluating choice navigation capabilities, the different set intersections illustrated in Figure 2 have been addressed individually. For each intersection, it is evaluated which metrics can support the assessment.

In intersection E the customer will start to configure a product, but never reach a final configuration which is purchased, although the solution space supports the requirements. This is difficult to distinguish from the case where requirements cannot be met within the existing solution space (intersection C), however it has been found that a high configuration abortion rate (CA) [19] metric can be used as an indication since customers that cannot configure a product to meet their requirements will likely abandon the configuration.

In intersection F the customers configure products which are within the customer demanded variety but outside the solution space, i.e. a product is configured which cannot be delivered. This would likely result in the order being cancelled by the company, since it cannot be manufactured. Alternatively, the company will change the configuration to fit within the solution space by e.g. upgrading the product. High values of Seller Order Cancellation rate (SOCR) [18] and Seller Order change rate after purchase (SOCRAP) [18] would indicate configurations within intersection F.

In intersection G the customer configures a product which is within solution space but does not correspond to the customer's requirements. In this case several things could happen. If the customer realizes that the product is not satisfactory prior to delivery, the customer may cancel the order or change the configuration which could be expressed as Customer Order Cancellation rate (COCR) [18] and Customer Order change rate after purchase (COCRAP) [18]. In other cases, customers will not realize that the configured product does not meet requirements, until it is received. In this case the customer may return the product which could be found as Customers Return Rate metric (RTR) [20] or complain (indicated by Customers Complaints Rate metric (COR) [19]). Also repurchase rates (RR) [20] metric and churn rates (CR) [5] metric would be expected as indicators. Configurations within intersection G are found to be indicated by high values of COCR, COCRAP, RTR, COR, and CR and low values of RR.

In intersection D the customer configures a product with properties that the customer does not have a demand for and is not part of the solution space. In this case either the customer or the company can react to this and either cancel or change the order. Hence configurations in intersection D will be indicated by High values of SOCR, SOCRAP, COCR and COCRAP. It may however be difficult to determine whether high values of SOCR and SOCRAP are due to configurations in intersection D or F. On the other hand, the customer does not receive the product no matter which are the configuration is in, so whether the customer had a demand for the product may be less important.

Since configurations within intersection A should lead to a sale, then an increase in Configuration sales rate metric (CSR) [18] would indicate an increase in configurations within intersection A.

2.2 Solution space development metrics

In order to establish metrics for solution space development and developing measurement techniques, it is important to have some sort of idea of what constitutes a "good" solution space or even an optimal solution space.

The optimality of a solution space can be described by defining two sets of products: 1) the different products offered by a mass customisation company, defined as the set SS (Solution Space) [16] and 2) the variety of products which are demanded by the customers, defined as the set CDV (Customer demanded variety) [16]. As illustrated in Figure 2, the intersection of the two sets will represent the products offered by the mass customisation company which correspond to products demanded by customers. The intersection of the two sets (A∩E) thus represents the products that customers may buy, given they are able to find and configure the products and willing to pay the required sales price.

The metrics for assessing a company's solution space as well as their solution space development capabilities need to reflect the requirements described above. The metrics are divided in five categories depending on what they are intended to measure. These categories are shown in Figure 3 and described in the following along with the specific metrics.

Within the profitability category, it has not been possible to identify metrics in the literature. What this category of metrics is supposed to measure is how profitable the mass customized products are. The reason why this should be measured is the assumption that the capability for solution space development is a prerequisite for being a successful mass customizer, i.e. profitable mass customizer. Hence, a profitable product portfolio will indicate a well-developed solution space. The following metrics has been defined: Aggregate solution space profitability (ASSP) [16] is a measure of how

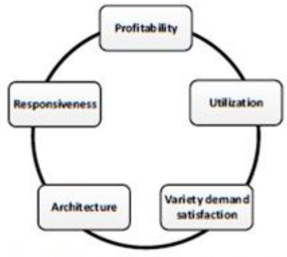

Figure 3: The five categories introduce to measure Solution Space Development.

profitable the solution space is as a whole and should be measured over a period of time, a metric measuring profitability per product family (PFP) [16], calculated similarly over a period of time and metric for Configuration Variable Profitability (CVP) [16], which is somewhat less trivial to determine. However if historical configuration data is available with sales price and manufacturing costs registered for each configuration it is possible to generate a linear model describing the variation in price and cost from the configuration variables using the methods described by Brunoe & Nielsen [21]. What is also interesting is how many configuration variables (percentage) have negative profitability (NPCV) [16]. Obviously, this metric should be as low as possible, and will indicate how well a company is able to develop only configuration choices which are beneficial. Furthermore we propose a metric for the skewness of the distribution of profitability (CVPS) [16]. A positive skew will indicate that a few configuration variables are very profitable, whereas a negative skew would indicate that a number of configuration variables contribute significantly to a lower profitability.

The utilization category addresses how well the solution space is utilized by the customers, i.e. how much variety is offered vs. how much does actually make sense compared to the customers' requirements. This is what the metric defined by Piller [20] (referenced from [19]) called Used Variety (UV) is intended to measure. However, using this metric may be difficult in practice, since the number of perceived variants is not readily available. A more practical way of assessing the utilization would be to calculate the frequency by which each configuration variable is chosen by a customer. By dividing this by the frequency of which configurations are made in general, the percentage of configurations containing a certain configuration choice could be calculated, thereby describing the utilization of a certain configuration variable. If these percentages are analysed statistically, two metrics can be derived: Mean Configuration Variable Utilization Percentage (MCVUP) [16] and Configuration Variable Utilization Percentage Variance (CVUPV) [16]. These two metrics can provide insight into the magnitude and differences in frequently by which certain parts of the solution space are actually creating value for customers.

Sales are intuitively a metric that can be used to indicate how satisfied customers are with the variety offered by a company. However, sales can be influenced by many other factors than the solution space, e.g. marketing efforts, sales processes, pricing decisions etc. We do however believe that it can give some kind of indication.

The metric Repurchase rate (RR) [20] describes to what extent customers repurchases a product, or to what extent customers return to the mass customisation company to buy another product.

The metric configuration abortion rate (CAR) [19] can also be a measure of how satisfied the customers are with the offered variety. If a customer initiates a configuration and is not able to select the desired product properties, and is thus unsatisfied with the offered variety, that customer is likely to abandon the configuration and purchase a competing product. Hence, a high abortion rate could indicate that customers are dissatisfied with the offered variety and vice versa.

The product architecture is very central in solution space development, since good product architecture will greatly reduce development and manufacturing costs when increasing variety, whereas a suboptimal architecture will imply rapidly increasing costs when increasing product variety. Simply put, the product architecture allows efficient generation of product variants and this also indicates how efficient a company is at solution space development. Covered extensively in literature, several relevant metrics were found in the literature review. The multiple use metric (MU) [22] indicates how many modules are required to produce all variants within the solution space. However, as mentioned previously in this paper, this number may soar to astronomic numbers, rendering the metric less useful.

The modules commonality metric (MCM) [19] is a measure of how many modules are common to all variants relative to the total number of different modules. Generally a higher module commonality will indicate more efficient product architecture, since higher commonality will usually imply lower manufacturing and development costs. A metric for parts commonality (PC) [19] is used to measure the relationship between common parts and the total number of different parts in the same way as the module commonality metric. A high part commonality also indicates an efficient product architecture since that would imply higher purchasing volume for each different part further implying lower purchasing costs.

The metrics within the responsiveness category are intended to measure how fast a company is able to develop its solution space e.g. in response to changed market requirements. The first metric is the rate of which new configuration attributes are introduced (RNCA) [16]. This is determined by summing up the number of added configuration choices during a certain period. Similarly, the number of eliminated configuration attributes should be measured resulting in the metric (RECA) [16]. A high RNCA indicates that a company frequently introduces new options for customers and would indicate that the company reacts to a broad spectrum of changes in the market. A large difference between RNCA and RECA would indicate that the solution space is either growing or shrinking. The two metrics described above describe the change rate of the solution space, but not the lead time for changes, which is also essential when competing in a rapidly changing market. We therefore introduce a new metric called average lead time for configuration variable changes (ALCVC) [16].

2.3 Robust process design metrics

The most postponed manufacturing setup is expected to support highly robust manufacturing processes. A good indicator of robust process design is differentiation Point Index (DPI) [23]. The Setup Index (SI) [23] addresses the cost of setup of manufacturing processes compared to the total cost of a product, and is an indicator of a low robustness.

Metrics have been identified which are related to time performance of the manufacturing system, i.e. the Quality of Order Reception (QOR) [24], the Order Delay Time (ODT) [24] and Customisation Process Indicator (CPI), the latter indicates the relationship between the actual manufacturing time of a customized product and the time a customer is willing to wait for a custom product [24].

4.2 Intersection F

In this case, customers configure products which are within the customer demanded variety but outside the solution space, i.e. a product is configured which cannot be delivered. This would likely result in the order being cancelled by the company, since it cannot be manufactured. Alternatively, the company will change the configuration to fit within the solution space by e.g. upgrading the product. As an indicator for these configurations we introduce two new metrics:

Seller Order Cancellation rate (SOCR)

$$SOCR = \frac{number\ of\ orders\ cancelled\ by\ seller}{number\ of\ placed\ orders} \quad (7)$$

Seller Order change rate after purchase (SOCRAP)

$$SOCRAP = \frac{number\ of\ orders\ changed\ by\ seller}{number\ of\ placed\ orders} \quad (8)$$

High values of SOCR and SOCRAP would then indicate configurations within intersection F.

Configurations within intersection F as well as D would be a result of a faulty implementation of a configurator, since a configurator should ideally reflect the company's solution space or a subset of the solution space. Reaching configurations within intersection F and D is very undesirable, since it will lead to loss of credibility as well as a need for costly manual business processes to resolve the issue.

4.3 Intersection G

In this case, the customer configures a product which is within solution space but does not correspond to the customer's requirements. In this case several things could happen. If the customer realises that the product is not satisfactory prior to delivery, the customer may cancel the order or change the configuration. To indicate this, two new metrics are introduced:

Customer Order Cancellation rate (COCR)

$$COCR = \frac{number\ of\ orders\ cancelled\ by\ customer}{number\ of\ placed\ orders} \quad (9)$$

Customer Order change rate after purchase (COCRAP)

$$COCRAP = \frac{no.of\ orders\ changed\ by\ customer}{number\ of\ placed\ orders} \quad (10)$$

In other cases, customers will not realise that the configured product does not meet requirements, until it is received. In this case the customer may return the product (indicated by RTR) or complain (indicated by COR). Also repurchase rates (RR) and churn rates (CR) would be affected.

Hence configurations within intersection G would be indicated by high values of COCR, COCRAP, RTR and COR and CR and low values of RR.

4.4 Intersection D

In this intersection, the customer configures a product with properties that the customer does not have a demand for and is not part of the solution space. In this case either the customer or the company can react to this and either cancel or change the order. Hence configurations in intersection D will be indicated by High values of SOCR, SOCRAP, COCR and COCRAP. It may however be difficult to determine whether high values of SOCR and SOCRAP are due to configurations in intersection D or F. On the other hand, the customer does not receive the product no matter which are the configuration is in, so whether the customer had a demand for the product may be less important.

4.5 Intersection A

Basically, sales within intersection A are the optimal solution, since products are sold within the solution space which also match the customers' requirements. Hence if there is little indication of configurations outside intersection A, then that should indicate that configurations are within intersection A. Since configurations within intersection A should lead to a sale, then an increase in CSR would also indicate an increase in configurations within intersection A.

Configuration sales rate metric(CSR)

$$CSR = \frac{number\ of\ sold\ configurations}{number\ of\ started\ configurations} \quad (11)$$

4.6 Further metrics

Apart from the metrics which relate directly to the intersections A-G, we identified a number of metrics which may be used to explain why configurations occur in intersections outside intersection A. Hence the metrics can be used to explain the possible reasons for a problem with a configuration system rather than whether there is in fact a problem.

Configuration click index metrics(CI)

$$\mathrm{CI}_c = \frac{\sum_1^n C}{V} \quad (12)$$

CI_c: *clicks index of configuration*
n: *numberofconfiguration in index (min 100)*
C: *number of clicks used for configuration i*
V: *numbers of outcome of variables*

CI metric is a measure of the number of selections, choices or clicks the customer makes in the configurator; or in other words the effort needed by the customer for performing the configuration. It could be the number of selections or actions which the customer has made for a number of given configurations indexed with the total number of variables available in the configurator. The metric cannot be used as benchmark in general or as comparison to other companies/configurators but it can be used internally as an indicator for how a change due to implementation of new variables in the configurator or change of configurator has impacted the choice navigation performance. Increase of CI may indicate more complex choice navigation or an increase in burden of choice navigation. In a broad view it can be argued that a a value of CI at or near one may indicate a perfect choice navigation.

Time used in configuration index metric(TI)

$$\mathrm{TI}_c = \frac{\sum_1^n T}{V} \quad (13)$$

TI_c: *configuration time index*
n: *numberofconfiguration in index* (min 100)
T: *time in seconds used for configuration*
V: *numbers of outcome of variables*

As for CI the TI metrics gives an index of the time used for a number of given configurations. As for CI the TI may be used internally as an indication of change in burden of choice caused by change of variables and/or change of configurator.

Some of the metrics defined in MC500[Walcher & Piller, 2011] can also be utilized as metrics in this context. However only the objective metrics are included here, and thereby not the metrics that are based on a subjective evaluation. The included metrics are:

- Visual features
- Navigation help
- Company help
- Customer help

All of these metrics are indicators of how customers are guided or helped through the configuration process. Given a company finds that many configurations are observed in intersections E or G, then looking into these metrics may explain the reasons for this.

5 Conclusion & Dicsussion

In order to support the development of choice navigation in mass customization and thereby also product configuration, metrics are needed in order to assess the choice navigation performance. To establish these metrics, relevant literature was reviewed and several applicable metrics were identified. Further metrics were defined in areas where no sufficient metrics could be identified in literature. The following list compiles the metrics identified in literature and newly defined metrics within choice navigation:

Metrics identified in the literature

- Configuration abortion rate metric (CA)
- Customers Return Rate metric (RTR)
- Customers Churn Rate metric (CR)
- Customers Repurchase Rate metric (RR)
- Customers Complaints Rate metric (COR)

Newly defined metrics

- Seller Order Cancellation rate (SOCR)
- Seller Order change rate after purchase (SOCRAP)
- Customer Order Cancellation rate (COCR)
- Customer Order change rate after purchase (COCRAP)
- Configuration sales rate metric(CSR)

It is the intention that these metrics can be used in MC companies for different purposes. One purpose is benchmarking against "best practice" mass customizers, in order to identify areas with the greatest potential for improvement. Another purpose is to use these metrics as key performance indicators which are continually calculated to monitor performance to continuously improve. In relation to research in mass customization it is the intention to apply these metrics in different types of mass customization companies to analyze what distinguishes successful mass customizers.

It is evident that the application of these metrics poses certain requirements related to data availability and quality. However, most MC companies already have systems in place which are very likely to contain the data required for calculating the metrics presented in this paper.

As mentioned in the introduction, choice navigation is one of three fundamental capabilities for successful mass customizers; the other two being robust process design and solution space development. There are strong relations between these three capabilities, and phenomena experienced in a company cannot necessarily be attributed to only one capability, and as such, the metrics defined in this paper can also be influenced by other factors than the solution space development capability.

One example is the metric configuration abortion rate which we argue indicates how well choice navigation is implemented. However, the configuration abortion rate will be strongly influenced by the solution space, i.e. how well the offered variety matches the demanded variety. The value of this metric can thus both be influenced by a company's performance within choice navigation as well as solution space development. In future research, metrics for the other two capabilities, Robust Process Design and Solution Space Development should be established and the links between all three capabilities can be analyzed. Furthermore, the relations between metrics performance and specific methods should be addressed so that an assessment could point out not only what a company should do to improve but also how.

When performing an assessment and interpreting the values of the metrics, the interpretation should take into account the product type. Also when benchmarking, different products cannot necessarily be compared directly. The reason for this is that several metrics are based on the customers actions, and these actions will depend on the product type. For exampe if a customer buys a customized car compared to a customized bag of muesli, then the customer would probably be more likely to complain or return the car if it has a wrong color compared to the muesli, if a wrong ingredient has been added. In that case, the difference would be due to the dfference in cost of the products. Furthermore a metric like the repurchase rate makes more sense for some product types than others. For example, customers are likely to repurchase muesli more often than cars. So this metric would depend on to what extent a product can be characterised as a consumable or a

Although these metrics are not direct indicators of process robustness, it is expected that highly robust manufacturing processes will have a good time performance and good performance within these metrics will indicate robust processes.

The metric Number of different modules manufactured per process (NMP) [17] gives a measure of the average number of modules manufactured in the different manufacturing processes; a higher NMP will indicate robust processes, since each process will be able to manufacture more different modules and thus a higher number of end variants.

The metric Degree of manual labour (DML) [17] can be used as an indirect indicator of process robustness, since a low need for manual processing will indicate that the non-manual manufacturing processes are able to supply a high variety.

Setup Index (SI) is the cost of setup of manufacturing processes is considered good measures of process robustness towards new variety. Process variety increase (PVI) [17] indicates how much the variety of manufacturing processes increases when a new product option or product is introduced in the manufacturing system. The PVI metric, calculated as an average during a period in time, a low PVI will indicate a high robustness since this implies that few new processes need to be introduced when a product option is introduced and thus that the existing processes can accommodate new product variety. The capacity expense (CAPEX) increase when introducing a new option is introduced (CAPIV) [17]. This is done since a high PVI does not necessarily come a high cost, given a new process is implemented on existing flexible equipment. The CAPIV metric is calculated as an average over a period of time.

The time and cost to introduce new product variety are also important metrics to assess process robustness, since robust processes will imply low cost and fast introduction of new product variety. The metrics Time to introduce a new option in the manufacturing system (TIV) [17] and Cost of introducing a new option in the manufacturing system (CIV) [17] have been defined.

3 DISCUSSION

It is evident that the application of these metrics poses certain requirements related to data availability and quality. However, most mass customisation companies already have systems in place which are very likely to contain the data required for calculating the metrics presented in this paper.

There are strong relations between these three capabilities, and phenomena experienced in a company cannot necessarily be attributed to only one capability. If for instance the profitability of the solution space changes, instead of changes in the solution space, it could be due to changes in the manufacturing processes lowering manufacturing costs or changes in choice navigation leading customers to choose products sold at a greater price.

One example is the metric configuration abortion rate which we argue indicates how well choice navigation is implemented. However, the configuration abortion rate will be strongly influenced by the solution space, i.e. how well the offered variety matches the demanded variety. In future research the relationship between the capabilities should be established and the links between all three capabilities need to be analysed. Furthermore, the relations between metrics performance and specific methods should be addressed so that an assessment could point out not only what a company should do to improve but also how.

When performing an assessment and interpreting the values of the metrics, the interpretation should take into account the product type. Also when benchmarking, companies manufacturing different products cannot necessarily be compared directly. The reason for this is that several metrics are based on the customers' actions, and these actions will depend on the product type. For example a customer buys a customized car compared to a customized bag of muesli, the customer would probably then be more likely to complain or return the car if it has a wrong colour compared to the muesli, if a wrong ingredient has been added. In that case, the difference would be due to the difference in cost of the products. Furthermore a metric like the repurchase rate makes more sense for some product types than others. For example, customers are likely to repurchase muesli more often than cars. So this metric would depend on to what extent a product can be characterized as a consumable or a durable, and in case it is a durable, how long the life cycle is.

4 CONCLUSION

In order to support the development of production in mass customisation, metrics are needed in order make performance measurement, assessment and benchmarking. To establish these metrics, relevant literature has been reviewed and several applicable metrics has been identified. Further metrics have been defined in areas where no sufficient metrics could be identified in literature.

In relation to research in mass customisation it is the intention to apply these metrics in different types of mass customisation companies to analyse what distinguishes successful mass customizers. It is the intention that these metrics can be used in mass customisation companies for different purposes. One purpose is benchmarking against "best practice" mass customizers, in order to identify areas with the greatest potential for improvement. Another purpose is to use these metrics as key performance indicators which are continually calculated to monitor performance to continuously improve.

This work concludes a preliminary research of assessment and measurement of the mass customisation process. We have with this paper finalized a general approach how to assess and measure mass customisation and set a framework of potential metrics, whether this is for the purpose of internally performance indicators or it is used for benchmarking in general. The next stage in this research will be test and evaluation of these potential useful metrics.

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This thesis addresses issues in management of mass customization: 1) the ability to assess and measure mass customization progress, 2) to what degree mass customization supplement sustainable product design.

Mass customization is a business strategy to approach customers with one of kind products. Following a mass customization strategy, business managers have several pitfalls and barriers to become and maintain being a mass customizer. A recent survey has addressed these barriers in being a mass customizer and exposes a substantial 17 % unsuccessful companies failing the mass customization business strategy within the first year. In the list of unrewarding mass customizers is well known jeans company Levi Strauss & Co.

This thesis presents metrics, which support assessment and measurement within three fundamental mass customization capabilities in given areas of the mass customization progress. The data for these metrics are based on availability in currently used IT systems, which makes the metrics useful for industrial applications.

MASS CUSTOMIZATION

ASSESSMENT AND MEASUREMENT FRAMEWORK FOR INDUSTRIAL APPLICATIONS

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